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Vibration monitoring of a gear grinding process

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VIBRATION MONITORING OF A GEAR GRINDING PROCESS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

by
Nandeesh Kadengodlu
August 2017

Accepted by:
Dr Gregory Mocko, Committee Chair
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ABSTRACT

Gear grinding is a process used to improve the surface finish of machined gears to increase their lifespan and decrease noise during their operation. Large scale gear grinding produces finished gears at a competitive cost but tool wear plays an important factor in the final quality. The objective of this research is to identify how process parameters during the gear grinding process vary and determine if they can predict the noise associated with gears in final assembly.

Specifically, this research records the vibrations on the grinding wheel and decomposes them using a Fast Fourier Transform (FFT). The vibration patterns at the grinding wheel mesh frequency are studied using two design variables that characterize the tool, a) grinding wheel diameter (d) and b) location along the grinding wheel width (y). These variables correspond to geometrical positions on the tool over its lifetime. This was followed by measuring parts machined at sections of the grinding wheel (varying y values) that recorded the highest and lowest vibrations to evaluate if the vibrations influenced the surface finish of the gears. Finally the gears are installed in gearboxes and tested for noise made due to running gears to evaluate if there was a difference in noise based on the gear geometries and the machining location on the tool

Analyzing vibration data for 2868 parts machined using a full tool, the results of an ANOVA and two sample t-tests showed a statistical difference between the vibrations recorded at different sections of the grinding wheel. Vibrations at y_4 are higher than the vibrations at y_{34} by 3.035 mg while vibrations at y_4 are higher than the vibrations at y_3 by 2.12 mg. Analyzing the geometrical data for 313 gears over four y locations, the results

show that the surface roughness of left gear profiles machined at y4 is greater than left gear profiles machined at y34 by 0.458 microns. The roughness of left gear profiles machined at y4 is greater than the left gear profiles machined at y3 by 0.167 microns. Additionally, the roughness of right profiles machined at y4 were lesser than those machined at y34 by 0.175 microns. Finally, 294 gears were tested in gearboxes and the statistical results show that gears machined at y4 were louder than gears machined at y34 by 1.088 dB while there was no statistical difference in noise made by gears machined at y4 and y3.

The future scope of this work will be to perform similar studies on different processes and determine if limits can be set to identify when rougher parts are machined and removed from serial production. This may also be achieved by taking samples from production failures and use them as a knowledge base to determine if quality can be determined by on-line monitoring systems.

DEDICATION

This thesis is dedicated to my parents who have always support my education and desire to constantly improve.

ACKNOWLEDGMENTS

I would like to thank all those involved in bringing this thesis to life and helping me see this through till the end

Dr Gregory Mocko for his guidance throughout the thesis and teaching me to ask the right questions while guiding my research methods

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CHAPTER ONE

INTRODUCTION

1.1 Manuscript Flowchart

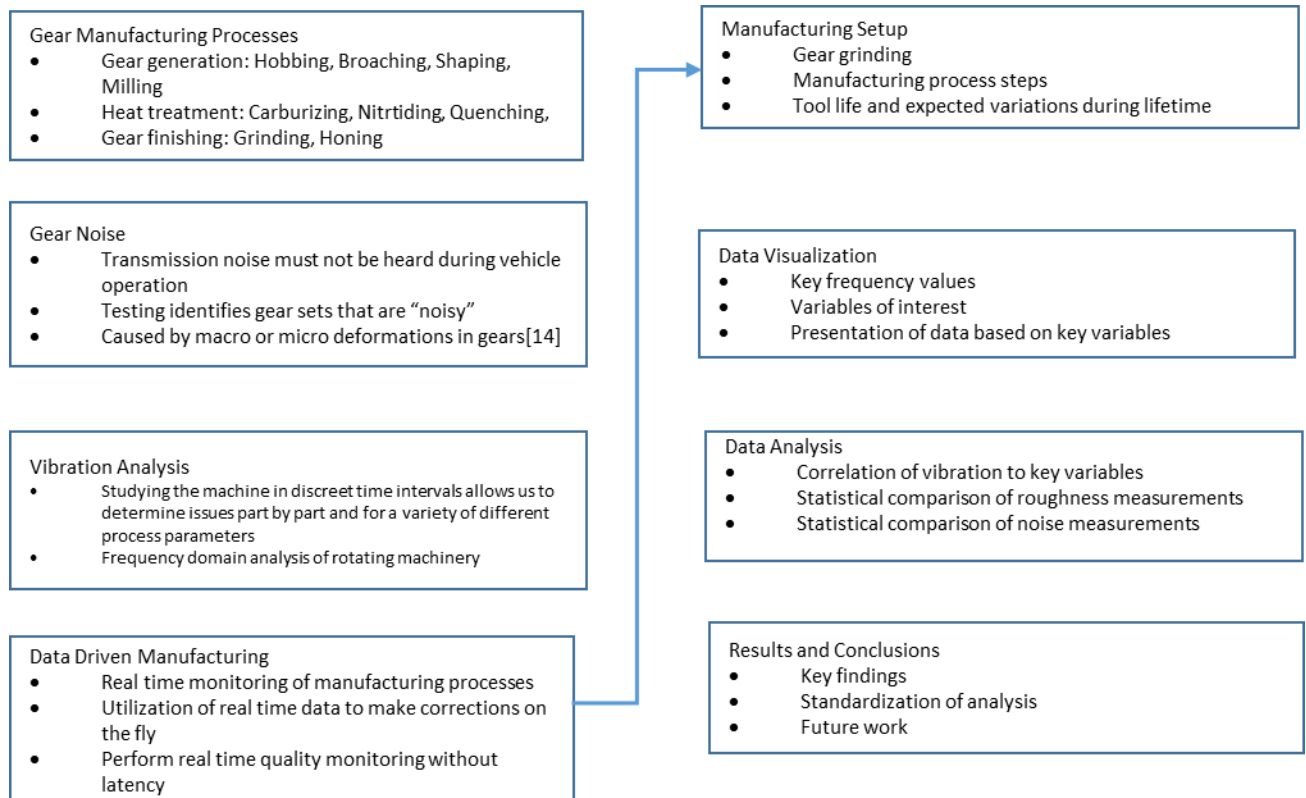


Figure 1: Thesis Outline

1.2 Research Objective

Traditional manufacturing environments focus on a balance of production and quality inspection frequencies. It is usually a compromise between high quality product and minimal quality inspection since quality usually takes time away from the line and is an reactive rather than proactive method of evaluation.

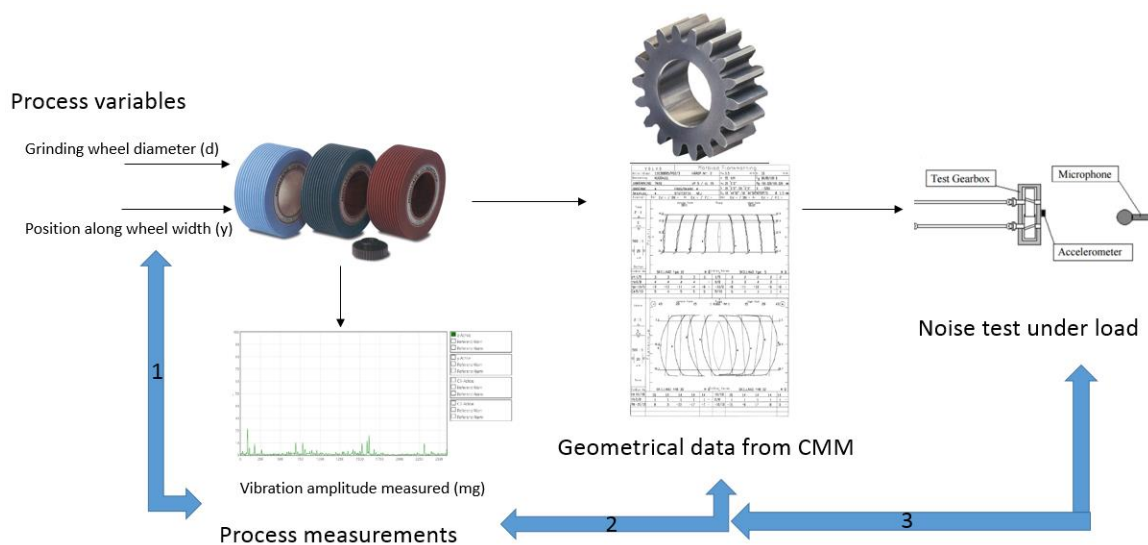


Figure 2: Flowchart of research objective

The goal of this research is to study the information available during gear machining and attempt to relate in-process manufacturing information to known quality defects. This will enable us to set limits on the machine that reject parts machined outside these limits and stop it from going downstream after it is rejected. Figure 2 shows the overall aim of the research with the three areas of focus highlighted as:

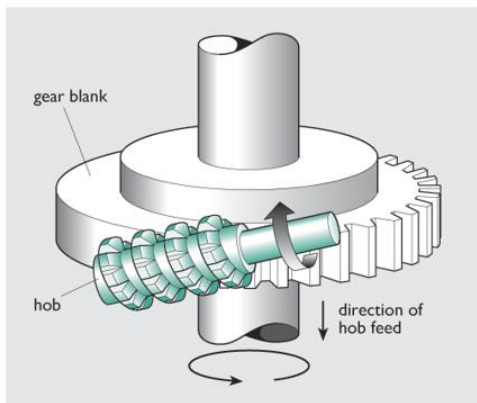
1. Study the link between process variables and process measurement of vibrations

2. Determine if the geometrical data can be correlated to process measurements using the process variables as a reference
3. Link geometrical data to noise under load and determine if it can be correlated back to process variables and process measurements

1.3 Gear Machining

There are many different operations that go into making a gear and each operation has many variants based on the quantity, quality, size and type of gear. The three main gear manufacturing steps are:

- *Gear Generation:* All machined gears start off as cylindrical blanks that are machined through a gear generation process such as hobbing, broaching, shaping and milling among other processes. These processes use tools designed to cut the profile and lead of a gear into the blank. The machined gear



(a)



(b)

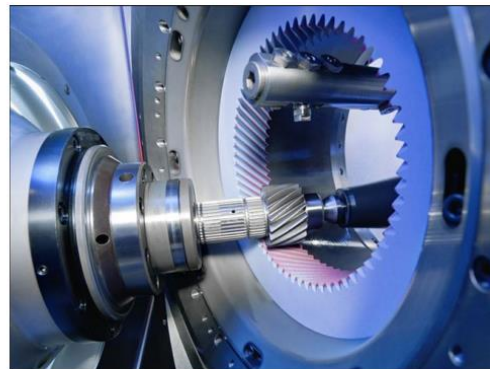
Figure 3: Gear generation (a) hobbing and (b) shaping

may be used directly or can undergo further processing in order to meet the design requirements.

- *Heat treatment:* It is common practice to generate the gear teeth while the blank is in its soft state to increase tool life and decrease residual stresses in the gear. This results in the need for further processing to increase the surface hardness and strength of the gear to meet the load and durability requirements of the design. A few of the heat treatment options are nitriding or carburizing, followed by quenching that imparts a case hardness on the surface increasing the lifetime of the gear through wear resistance and longer fatigue life. While the distortion caused by heat treatment can be controlled, it is common to further process the gears to reach the final geometry
- *Gear Finishing:* This process is used to finish hardened gears to the final tolerances as required by design. It generally involves controlled stock removal with finishing processes such as grinding or honing (Figure 4).



(a)



(b)

Figure 4: Gear finishing (a) grinding and (b) honing

1.4 Gear Grinding

Gear Grinding is performed with a grinding wheel that removes a very thin layer of the case hardening to generate the final profile. The wheel can either be a profile grinder where the CNC motion of the wheel generates the profile or the profile can be designed into the wheel and ground onto the gear. The latter involves grinding worms which are designed as the mating worm gear for the work-piece.

The grinding tool is often dressed with a diamond dressing wheel after a fixed number of work-pieces in order to sharpen the tool and ensure that the target gear geometries are met. While the amount of material removed from the wheel is less than a millimeter, the dressing process is very critical as any deviations is transferred to the work-piece leading to parts that are out of the design tolerances. While tool manufacturers design for such a variation, the combination of all machining parameters, work-piece parameters and machine properties occasionally leads to defects due to tool chatter or tool breakdown. This can be monitored using a live system that detects changes in the machining process and either alert the operator of the defect or reject the part machined under anomalous conditions in order to save on further processing costs.

1.5 Research Questions

Gear grinding is a common method utilized to mass manufacture gears for a variety of applications. The common practice is to utilize information supplied by machine manufacturers and tool suppliers based on their designs. It is useful for the gear manufacturer to understand how the tool behaves and the quality of gears machined by

unique combinations of machine, tools and processes. The aim of this study is to answer the following questions regarding serial production of gears:

1. Is there a variation of vibration measurements that correlate to the variables of the grinding wheel?
2. Is there a variation in the gear geometries that correlate to the location of machining on the grinding wheel?
3. Is there a variation in the noise made by gears that correlate to the location of machining on the grinding wheel?

CHAPTER TWO

LITERATURE REVIEW

2.1 Transmission Errors and Gear Noise

Gear noise has been the focus of many studies over the years and one of the causes for loud gears has been identified as transmission errors. In order to study transmission errors and gear noise, we must first understand these terms and the previous studies that investigate these phenomenon.

Gear noise is defined as the variation of amplitude, direction or position of forces at mesh by Smith [1]. The cause of these variations can be attributed to gear geometry, conditions of bearings and journals the gears are mounted on, resonance of gear rotational speed with machine components among other reasons. These variations are clubbed together as transmission errors (TE) by researchers studying gear noise.

Welbourne [2] defines TE as the difference between the actual position of the output gear and the position it would occupy if the gear drive was perfectly conjugate. In his study about gear errors and their resultant spectra [3], the fundamental assumption is that all gears must have errors and attempting to study the perfect gear is impractical. After looking at six different forms of transmission error, he concludes the focus of TE reduction should be the eccentricity of the base circle and the presence of harmonics of the error which is capable of resonating the system.

Smith [4] continued the study of measured gear noise and its relationship with transmission errors. He states that the key to understanding gear noise is the frequency domain. Figure 5 shows a frequency spectrum analysis of gear noise and highlights the

harmonics of mesh that are typically loudest in a gear. It also highlights the possibility of other peaks that are known as “ghost” harmonics since their source is unknown. Additionally, any run out in the gears, shafts, bearings or other rotating elements in the gearbox can lead to higher excitation at frequencies other than the mesh.

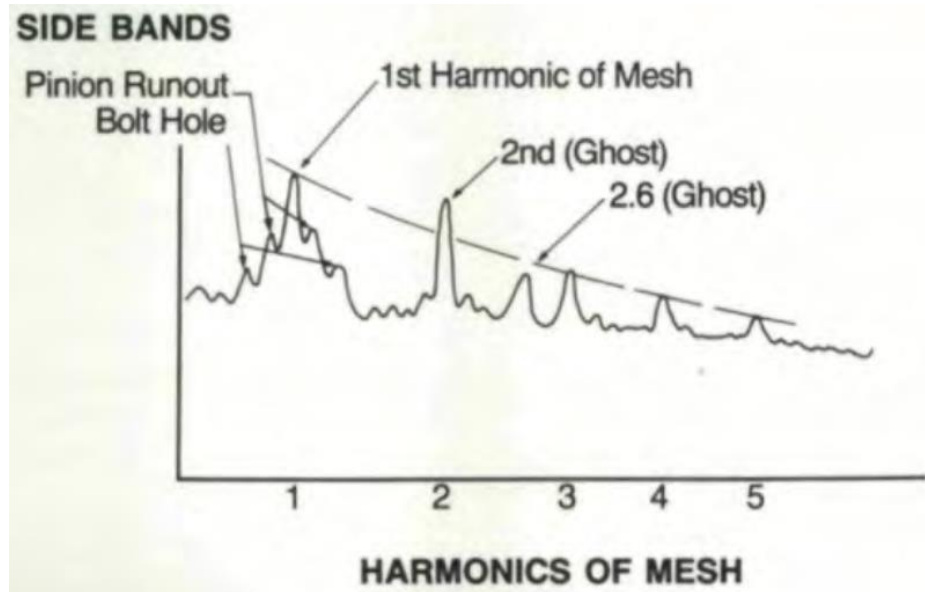


Figure 5: Frequency distribution showing mesh frequency and its harmonics [4]

Another key point in the paper by Smith is the need for an objective method of evaluating gear noise. His experiences showed either tests being performed subjectively with the tester rating the gear noise on a scale of 1-10 or instrumentation to record data and analyzed by NVH personnel unfamiliar with gear geometry and their effects on the peak vibration spectra. The study recommends the use of frequency discrimination to relate audible data to the graphic data of the frequency plots.

Davoli [5] uses carefully controlled profile modifications to study their effect on the noise of spur gears. The aim of the research is to determine if these profile modifications and similar geometrical deformations can be identified with the noise emission of the gear.

His study shows the measured TE has two components, the first one that increases with the applied torque and is uniform due to mean gear tooth deflection under load. The second component varies over the rotation of the gear due to variations in stiffness and gear geometry due to machining errors. The study concludes with the importance of using TE to validate the profile modifications defined during design and a combination of theoretical and simulations can be used to design quieter gears.

In order to determine the effect of transmission errors on the motion of gears, Munro [6] tests methods of evaluating TE based on different applications of gears such as their use in precise indexing operations or vibration and noise studies. His method tests gears using single and double flank checkers with master gears in order to accurately determine TE for different types of gears. His conclusion claims that the single flank method of checking for TE is likely to rise in importance

A more recent paper by Gravel [7] evaluates deviations on a gear using an evaluation method that calculates the amplitude of dominant frequencies picked up from gears. His method utilizes measurement values from gear measuring devices available from production measurements. The values are translated from compensating sine wave functions that are overlapped on the gears rotational path. Figure 6 shows the plane of action along which the profile traces are overlaid to simulate the ripples or deviations seen along the rotational angle. While this evaluation can be performed with measurements from a few teeth, for best results, all teeth must be measured.

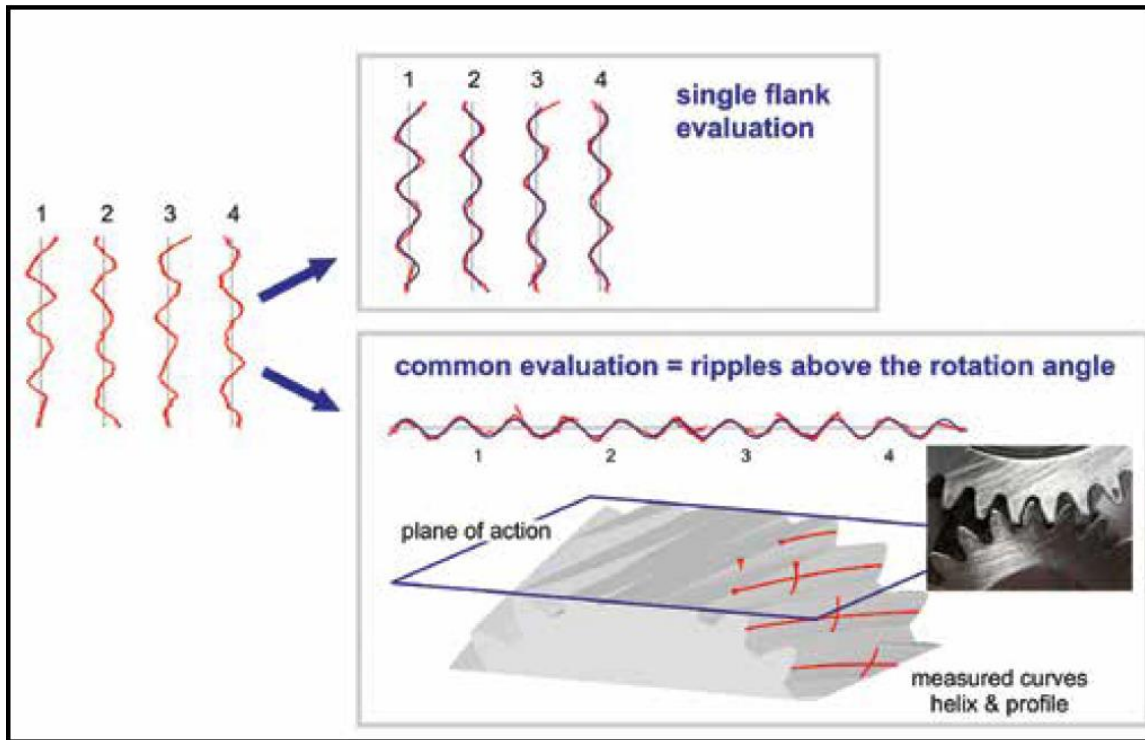


Figure 6: Analysis of ripples due to profile deviations [7]

In a gear noise and vibration review, Akerblom [8] shows that geometrical errors such as involute and lead deviations are a source of transmission errors. Since the processes used to manufacture gears are imperfect, there will be a deviation from the theoretical gear profile. His study of gear noise and vibrations [9] utilizes different gear finishing methods and measures the TE for gears with different profile modifications. While his study finds that the noise signature changes for the same gear pair if disassembled and reassembled, he concludes that factors like threaded wheel grinding decreases gear noise while an increase in surface roughness increases gear noise, among other factors

Bonori and Pellicano [10] study the effect of randomized profile and lead deviations on the dynamics of spur gears when compared to the ideal gear teeth. Figure 7 shows the

result of manufacturing errors on the contact area during mesh. Depending on the extent of the error, there may be a lack of material to contact smoothly during mesh or there may be an excess of material leading to interference. The study creates a gear with a randomized profile for all teeth of a gear as shown in Figure 8. The tolerance is indicated by the dotted lines giving a bounded area for the simulated gear profile. The tolerance is non-uniform throughout the gear profile to account for the tooth and root relief required for smooth mesh and increased durability of the gear.

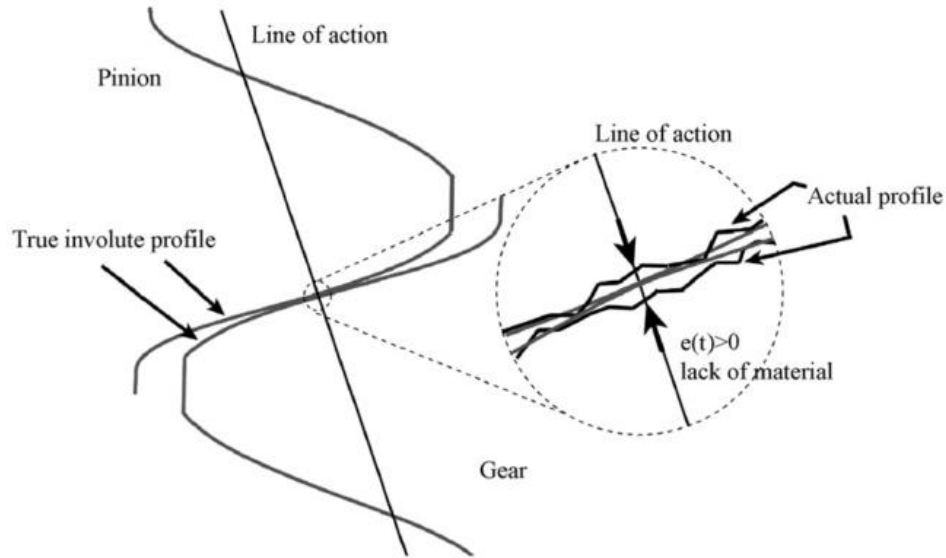


Figure 7: Visualization of profile error during mesh [10]

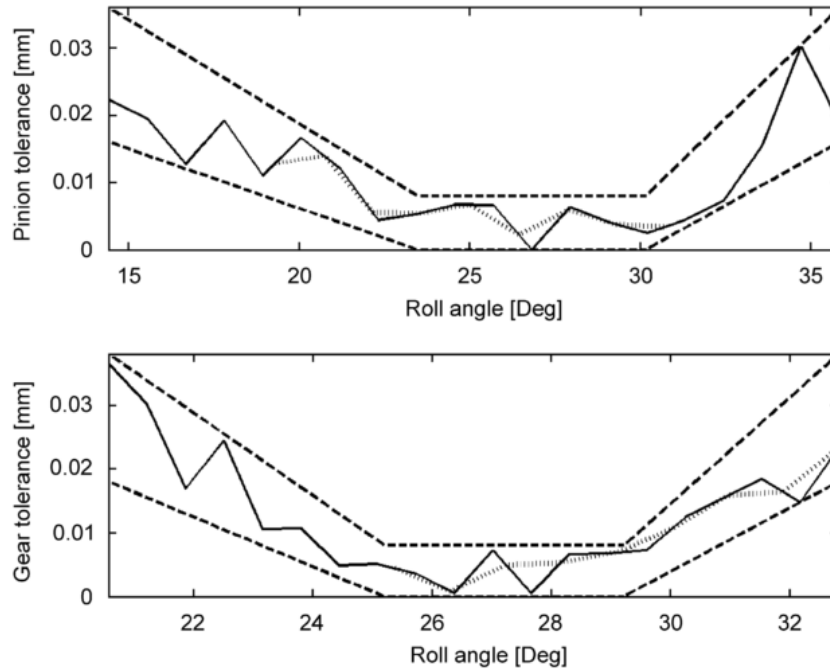


Figure 8: Computer generated profile errors [10]

They conclude by stating the presence of manufacturing errors magnifies the amplitude of vibration and the frequency spectrum response is linked to the nature of the error. It is also claimed that slightly different profile errors, within the same tolerance class, can lead to non-negligible differences in vibration amplitude.

Dale [11] studies the nature of gear noise and the possibility of detecting transmission errors using gear noise. In his study, the frequency spectra is seen to be an inadequate method of determining gear noise due to the presence of sidebands. These sidebands are found at frequencies other than the fundamental frequency and its harmonics. To distinguish between the fundamental frequencies and the sidebands, he utilizes an order based analysis where data is sampled at fixed intervals of rotation instead of fixed intervals of time. This converts the frequency axis into a cycle per revolution, also known as, an

order. He concludes by stating additional work is necessary to demodulate the signals and isolate transmission errors from gear excitation.

Frolov [12] studies the control of gear vibrations at their source and investigates the factors affecting the mesh frequency and its harmonics. He determines the primary exciting factors in the mesh frequency range are the mesh stiffness variation and the pitch error. The solution recommended to drive down gear vibrations includes high precision manufacturing and profile modifications to drive down variation and profile error and reduce the possibility of gear vibrations.

Oswald [13] utilizes a test rig to validate a boundary element method for acoustic prediction (BEMAP) for helicopter transmissions. The aim was to validate the BEMAP code in order to utilize it in the design phase of transmission design and reduce the acoustic intensity of the transmission after manufacture. The experimental setup was limited to frequencies above 400 Hz due to contamination of measurements in acoustic absorption. The study concluded by determining the computed spectral traces for sound were similar to the spectra of measured sound power. These tests were compared at the gear mesh frequencies and the modal resonance frequencies.

These studies show that transmission error and deviations from nominal gear profile are a common source of gear noise. The cause of the deviations can be attributed to wear, improper mounting, or manufacturing errors to name a few. The noise made by gears with these errors are seen in the mesh frequency of the gear pair or its harmonics depending on the nature of the error. These studies can be used to determine if noise made by gears with

particular profile deviations are machined with similar or dissimilar process parameters to deduce either their source or a method of identification during machining.

2.2 Vibration Monitoring Systems

The role of natural frequencies and excessive vibration in determining the quality of transmissions have been a key point of research for decades. Past studies have attempted to predict gear quality, detect failure, and recommend maintenance schedules based on monitoring systems during operation rather than bring them offline and increase downtime.

A study by Ognajovic and Subic [14] attributes gear vibration to two main parameters : Macro and micro geometry. Macro geometric parameters are based on the gears overall dimensions such as gear diameter, width, number of teeth and so on. These dimensions are calculated based on the selection of material, tooth impact velocities, excitation frequencies, tooth stress, and so on. These dimensions should meet the requirements for load and durability of the gear as well as reduce the possibility of vibrations in the system. Micro geometric parameters refer to the difference between the theoretical and actual position of the points of contact along the gear tooth. These deviations can be caused due to the elastic deformations for the tooth or due to the manufacturing uncertainties.

A recent study by Hagan [15] looks at the role natural frequencies play during a grinding operation. He looks into the effects of machining parts at speeds close to the natural frequency of the machine and discovers there is an increased vibration amplitude seen which results in chatter on the work piece. The study concludes that there must be

proactive measurement to track machine vibration. This will help in avoiding process settings that are close to natural frequencies of the machine.

Hassui [16] evaluates the vibration signals observed during grinding wheel wear in an attempt to determine the tool life. His study determines the average roughness of the work piece increases with the material removed and thus the grinding wheel wear. This in turn results in a higher vibration amplitude seen on the tailstock. It concludes by claiming the claimed tool life can be improved with a better signal conditioning algorithm.

Since gear grinding is often the final step in gear machining, the process must be controlled to keep deviations to a minimum. The two most common forms of grinding are profile grinding and continuous generation grinding [17]. While both processes use a vitrified grinding wheel, the continuous generation grinding can be described as a worm-worm wheel arrangement where the grinding wheel or worm moves tangentially to the work-piece while generating the gear tooth profile. The grinding worm shifts tangentially after a fixed duration such that a fresh part of the wheel is processing the work-piece and once the entire width is used up, the wheel is dressed with a diamond roll by removing stock material from the grinding wheel and exposing a fresh layer of grain. This process is repeated till the grinding wheel is all used up [18].

Researchers have used the vibration signatures of gearboxes and rotating machinery to determine the health of the machine. This application is used for critical elements such as gearboxes in the aerospace industry or rotating shafts and turbines in a power generation facility. The following studies explain the use of vibration analysis to detect the development of faults in rotating elements of a machine.

Li [19] explores the use of time domain and frequency domain analysis to determine spalling in the gearbox of a turbojet engine. The study uses a time synchronous averaging (TSA) method of extracting periodic waveforms from the raw signal of rotating components. The TSA signals are then transformed into the frequency domain through the use of Fast Fourier Transforms (FFT). In order to accommodate resampling the frequency spectrum is transformed into an order using the reference frequency of a selected shaft. The study concludes that the use of a spectrum and order based analysis is robust enough to detect changes in loads and the gear mesh properties.

Patil [20] uses FFTs to study defects on electrical machinery and a single gear pair rotating on the output of the motor. Figure 9 shows the FFT plot of the motor under normal operating conditions vs the vibrations experienced when the system is imbalanced. Figure 10 also shows the response observed when one of the gears is replaced with a gear with a broken tooth. It is seen that the vibration signals change with change in system properties and the use of vibration analysis in fault detection can be explored further.

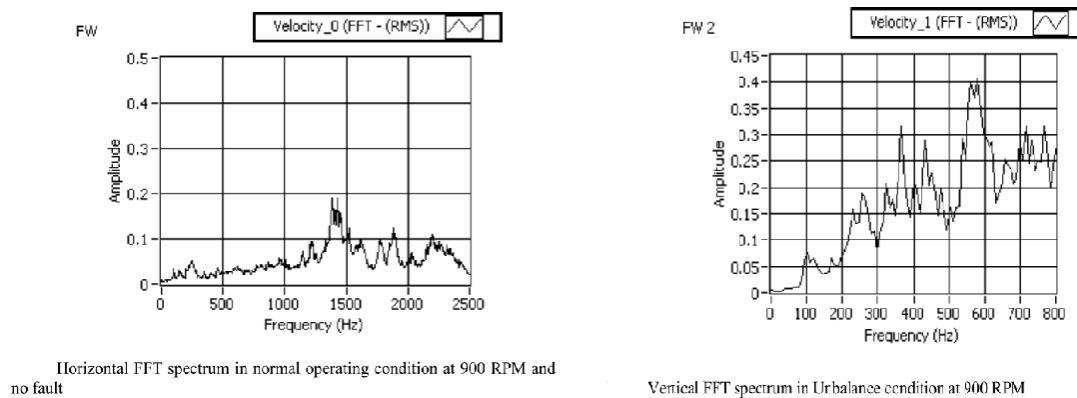


Figure 9: Horizontal and vertical FFT spectra for good rotating elements [20]

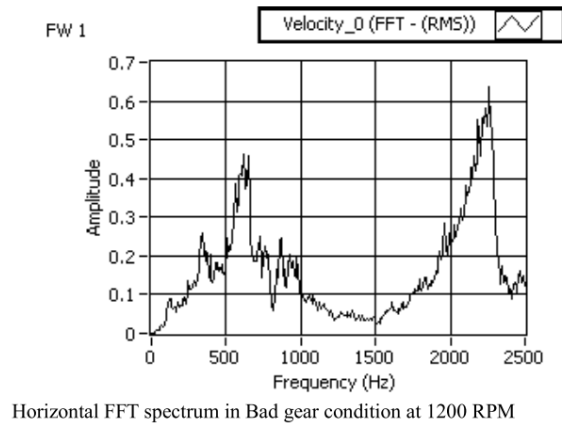


Figure 10: FFT spectrum for bad rotating elements[20]

The aim of this thesis is to study the vibration signatures seen on a grinding wheel over its lifetime and determine if they can be related to gears that deviate from the nominal and result in micro geometric transmission errors. The use of natural frequencies from vibration amplitudes resolved into FFT can provide a lot of data on the nature of the process and determine if any significant change to the machine occurs due to wear. These concepts can be used to isolate deviations from expected operating conditions and direct the investigation in the right direction.

2.3. Data Driven Manufacturing

Quality departments in the manufacturing world are largely reactive system rather than proactive. The machined parts are checked on a co-ordinate measuring machine (CMM) at fixed intervals and if the part meets the tolerance level, the batches produced before it are released. If the part is out of tolerance, the engineers make decisions based on the policies of the production facility. With the development of internet of things and

industry 4.0, manufacturing facilities are built with live monitoring systems in place and the ability of the system to identify faults and direct maintenance efforts to areas of immediate need. This is facilitated by a myriad of sensors in the equipment and the challenge is to not only narrow the kind of data monitoring systems employed but also the method of data analysis. This glut of data presents a different kind of problem where data mining and analysis techniques have to be optimized to the process being monitored.

To draw a picture of the vision of industry 4.0, Bosch released a white paper titled Industrial Internet: Putting the vision into practice [21]. They use the terms Industry 4.0 and the Industrial Internet synonymously and term this as the fourth paradigm shift in production. The idea is to have machinery manufacturers develop new business models where the service offered creates greater margins for the company. This is achieved by connecting machines in the field and access machine data during real time production. The proliferation of sensors and software is the first step in achieving the industrial internet leading to large scale data collection.

Once the data is gathered, the next aim is to make meaningful conclusions about the process. In order to drive down costs, data analytics must be used to model and acquire knowledge to determine patterns and develop predictive models. This can be used for a wide range of maintenance efforts such as improvement of process quality and detection of wear and its consequences. This paper is indicative of how the industrial internet can combine with existing analytical techniques and utilize large scale data acquisition to reduce manufacturing costs.

Harding [22] reviews data mining techniques that can be used in the manufacturing sector. His method reviews the two knowledge based models, the first dealing with a conventional transformation of data into knowledge. The second model is a reverse method where knowledge drives data gathering and information processing. His review looks at the use of data mining complementary tools such as decision support systems, quality improvement and fault detection in different manufacturing applications. The review covers data mining techniques by Maki [23,24] that talks both about automating the data collection through the use of computers on the shop floor and feature extraction for further analysis of probable defects.

The use of decision support systems with tools such as on line analytical processing by Bolloju [25] in order to convert tacit knowledge to explicit knowledge (Figure 11) enhances decision making abilities and allows for limits to be set based on existing knowledge of the process. These limits can then be looped back to the current production status and updated based on real time data

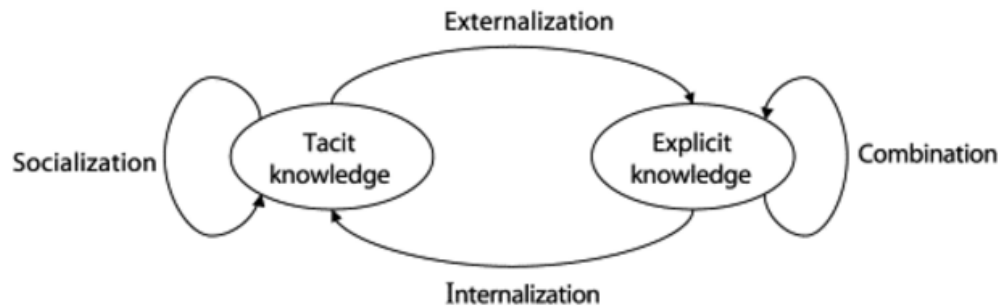


Figure 11: Transformation of implicit knowledge to explicit knowledge [25]

Another important tool in data driven manufacturing is fault detection that stops production or alerts operators of any faults that occur during the process. This step, when

combined with the previously mentioned methods allows for a system that learns when quality is reducing and makes changes accordingly. Harding concludes the review with the importance of the quality of data and the knowledge that is gained from data mining must be used in a productive manner.

2.4 Key Learning and Research Opportunities

Gear machining and studies involving gear noise have been around for decades. The use of vibration monitoring to diagnose gearbox life and faults has been explored thoroughly as well. The combination of the two to predict quality of gears before assembly is a relatively new field. Studies that monitor tool life and machine wear may be extended to make data driven decisions regarding the quality of gears machined using grinding wheels. Using on-line inspection will reduce downtime and catch poor quality gears before reaching the final product resulting in a cost of quality reduction along with an increase in productivity.

Using the concept of profile error deviations [26], we can determine the roughness of gear profiles. Additionally, monitoring systems may be used to evaluate vibration amplitudes during meshing frequencies of the gear pair and the gear grinding worm with the work-piece [11,12,15,27]. This combination of data, may allow us to characterize the grinding wheel in order to isolate variables during the machining process that allows for a in process quality monitoring system. At the very least, the analysis of the data will give us a better understanding of gear grinding processes and the knowledge that the process may or may not be perfect and delivering parts with the desired quality levels.

CHAPTER THREE

MANUFACTURING PROCESS

3.1 Gear Grinding Process

The gear grinding machine is a cylindrical grinder with two spindles. One spindle is being worked on while the other is used for loading and unloading the work-piece. The work-piece is located with an automatic meshing sensor in order to locate the teeth and synchronize with the grinding wheel. The grinding wheel is mounted on a moving head (as shown in Figure (12)) that spins the grinding wheel and is free to move in the x, y & z coordinates while swiveling along the y axis. The construction of the grinding machine results in the grinding wheel supported like a cantilever beam.

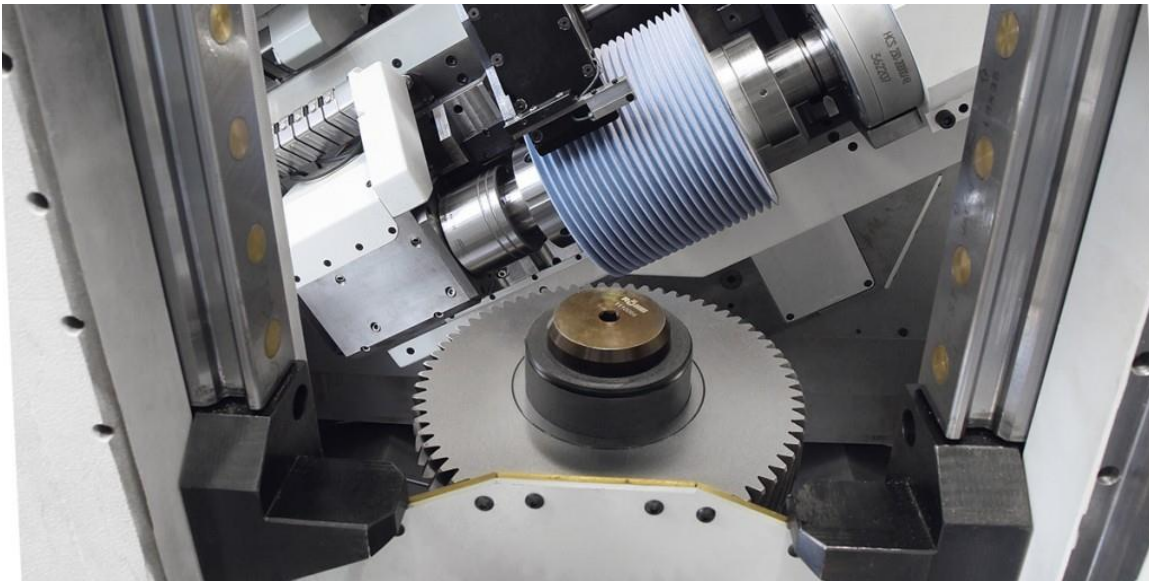


Figure 12: Gear grinding head

The two controlled variables of interest in the grinding process are the grinding wheel diameter and the y-position of the grinding wheel width. Figure 13 shows the directions in which these variables are measured.

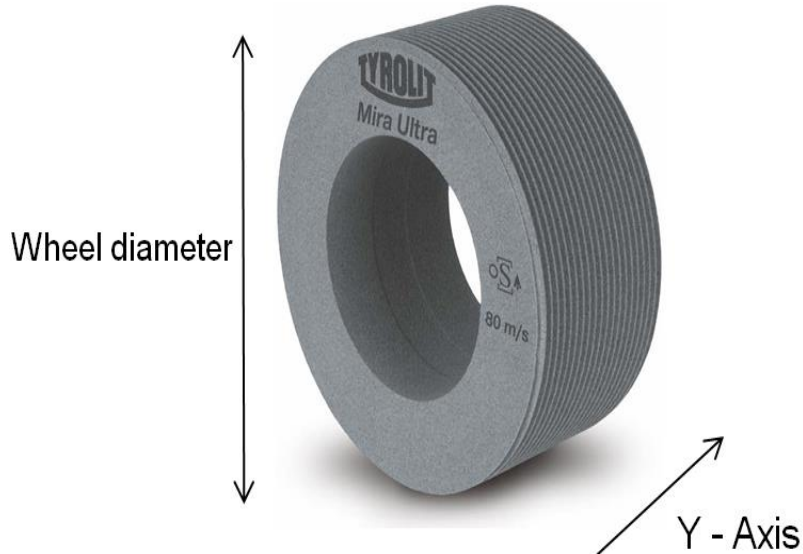


Figure 13: Gear grinding wheel indicating key variables

When the wheel is new, the first part is machined at $y = y_1$ and $d = d_1$. Depending on the process, the machining cycle involves 2 or 3 passes with the last pass finishing the gear to the final specification. Once the part is finished, the wheel then indexes to $y = y_1$ until the wheel indexes to $y = y_n$, where n is the number of parts per dressing cycle and is set by the process. A result of the grinding wheel loaded as a cantilever is that the smallest y positions are towards the free end of the wheel while the largest y positions are towards the fixed end of the wheel supported by the spindle motor and the grinding head.

After the grinding width is used, the wheel is dressed and the diameter decreases by a small value (usually around 0.5 mm). The new diameter $d = d_2$ is then used from y_1

to y_n and the process continues until the grinding wheel reduces from $d = 275\text{mm}$ to $d = 220\text{mm}$.

The gear grinding process has many more variables during the machining process, and these will be considered either as a controlled variable or as an extraneous variable.

The controlled variables are:

- Number of starts on the grinding wheel
- RPM of the grinding wheel

The extraneous variables effect the process in such a way that their effect is hard to be negated in a systematic manner. A few of the extraneous variables are

- Defects on the spindles due to regular wear
- Source of the hobbed gears due to production scheduling

3.2 Vibration Data Collection

The machine is fitted with 4 accelerometers that measure the vibration experienced on the machine every 50 milliseconds. Two sensors are fitted on the grinding head with one sensor measuring the grinding wheel vibrations along the y-axis (axial) and the other on the z-axis (radial). The other two sensors are installed on the z-axis (radial) of each spindle. Figure 14 shows the location of the 4 sensors on the grinding head. Each sensor is connected to a PC or VSE unit which evaluates the FFT of the collected data and transfers it to a local PC dedicated to the vibration monitoring system. This local PC is the interface between the user and the sensors.

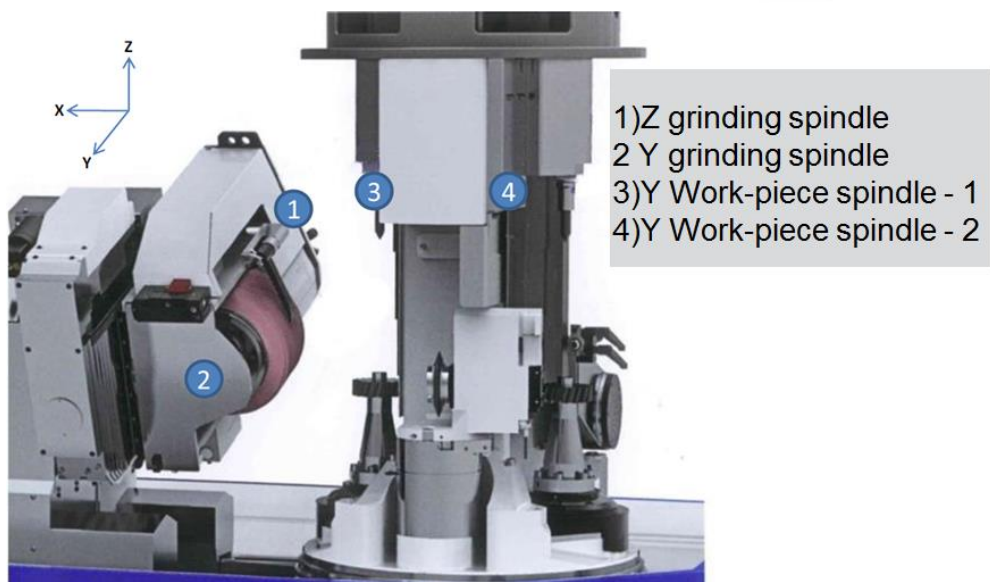


Figure 14: Grinding head with sensor locations

Figure 15 is a visual representation of the sensors connected to the network

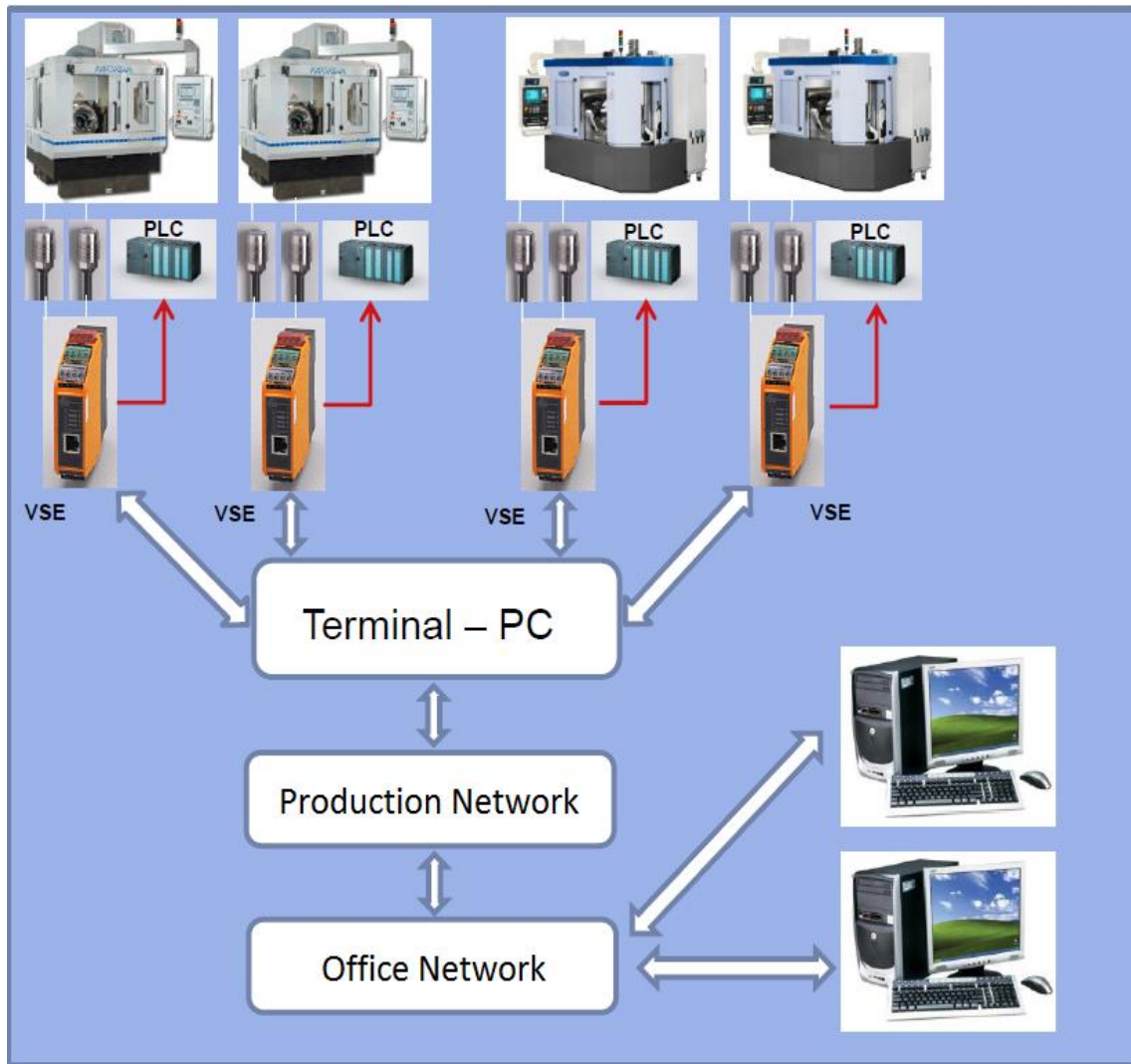


Figure 15: Sensor configuration in the network

The software interface allows the user to define the frequency resolution sampled and is limited to 850 spectral increments that multiply with the resolution to compute the FFT. The data is then written into a .csv file with header information containing different process variables such as the part number, grinding wheel RPM, work-piece RPM, number of starts in the grinding wheel to name a few. To differentiate between parts, the machine

utilizes a counter that increments at the end of the machining cycle. The counter is used to sort the data and distinguish the different measurements by part. The following Figure 16 shows a screenshot of the data captured by the sensor. The experimental variables of y position (y) and wheel diameter (d) are highlighted along with the frequency resolution. The value columns next to the y position are the start of the FFT values and the frequency of measurement can be calculated by equation 1

type	FFT
machinename	[REDACTED]
materialnumber	[REDACTED]
Device	192.168.214.100:3321
sensor	1
frequency resolution	3.051757813
spectrumcount	1
green	1
yellow	1
red	1
workstep	1
Nr of starts	3
Nr of teeth	22
Wheel-Diameter	274.9100037

Grinding Wheel Variables, y & d

Timestamp	Alarmlevel	Grinding		Y-Position	Value 1	Value 2	Value 3	Value 4
		Part Number	Wheel RPM					
1490193015826	1	0	0	5000	5000	5000	5000	5000
1490193015841	2	0	0	5000	5000	5000	5000	5000
1490193015107	0	18702	-5300	274.91	40.475	0	0.771	0.565
1490193015435	0	18702	-5300	274.91	40.475	0	1.136	1.286
1490193015779	0	18702	-5300	274.91	40.475	0	1.303	0.41
1490193016138	0	18702	-5300	274.91	40.475	0	1.199	0.107
1490193016466	0	18702	-5300	274.91	40.475	0	0.212	0.873
1490193016841	0	18702	-5300	274.91	40.475	0	0.569	0.834
1490193017169	0	18702	-5300	274.91	40.475	0	0.486	0.772
1490193017498	0	18702	-5300	274.91	40.475	0	0.681	0.734
1490193017841	0	18702	-5300	274.91	40.475	0	0.42	0.799
1490193018232	0	18702	-5300	274.91	40.475	0	0.75	1.214

Figure 16: Accelerometer data collection

$$Frequency = Value \# * Frequency Resolution \quad (1)$$

3.3 Sample selection for CMM and noise testing

The regular production cycle is set-up to grind a certain number of parts per grinding dressing cycle by shifting the grinding wheel along the y-axis as shown in Figure

13. After the current tool surface is all used up, the wheel is dressed and the process starts at the beginning of the grinding wheel width again. The machine is re-programmed to place up to 4 parts per dressing cycle into the drawer meant for SPC parts to be collected and analyzed in the gear lab. These parts are collected such that they represent the machining conditions at a particular location along the face width of the grinding wheel (y_n). Each part is scribed with a number that contains information such as machining time, machine number and spindle number. This lets us track the part through assembly and identify the vibration signatures that belong to the machining cycle of the individual part. The selection of parts along the y-axis is based on previously manufactured gears that were known to have quality issues.

3.4 Geometrical evaluation on CMMs

The gears that have been removed as a sample are now measured using CMMs that are designed to measure gears. The measurement programs are based on the target geometry desired on the gear and the manufacturing process completed. Depending on the size of the gear, the number of teeth to be measured are determined based on the time taken for measurement. The output of the measurement is a gear diagram as shown in Figure 17. The traces on the top represent the profile measurement and those on the bottom represent the lead measurement. The scales of each measurement are given on the left hand side of the diagram. The trace is transformed into a number of measurements such as angle deviations, form deviations, tooth modification measurements to name a few. The gear

diagram is then used to evaluate the quality of the gear and if any dimensions fall outside the desired specifications, the part is determined as o.T or out of tolerance.

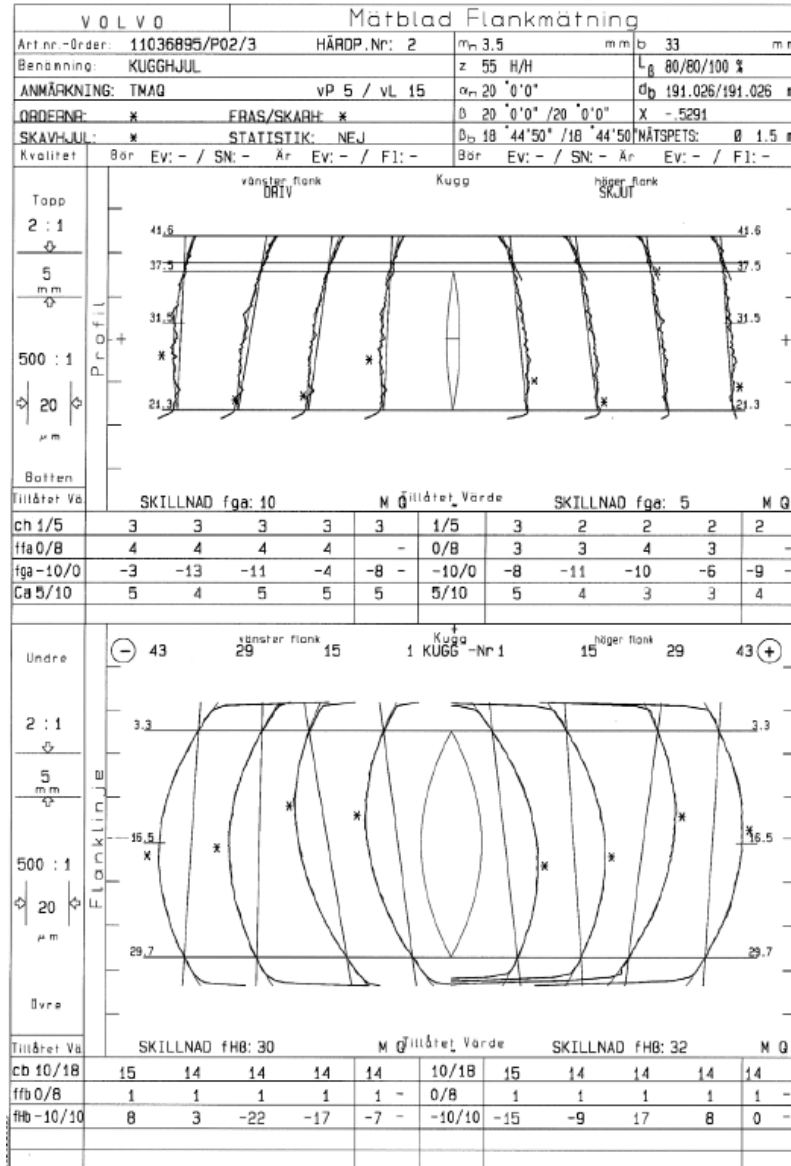


Figure 17: Gear diagram showing CMM measurements [8]

The measurements are recorded with increments of 0.1 microns. From literature, the result of TE can be due to micro geometrical deviations in the gear tooth. From the above gear

diagram, the value of the surface roughness is a known quantity and is reflective of the micro geometrical errors in the machined gear. The surface roughness of a gear tooth is defined as the difference between the highest and lowest point of the measurement as seen in Figure 18 [28]. While there is a designed tolerance for ideal manufacturing, phenomenon like waves and ripples are caused due to deviations in the machined gear that are within the set tolerance.

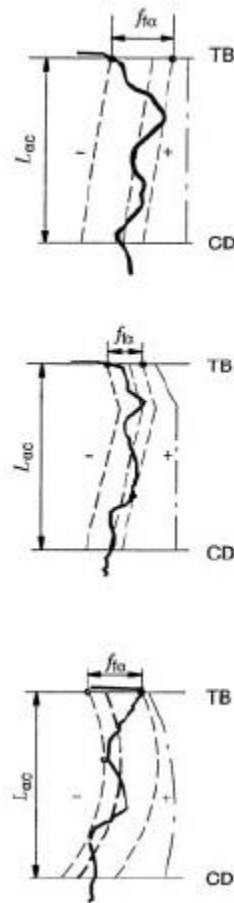


Figure 18: Surface roughness evaluation [28]

The measurement time is driven by the size of the gear due to the necessity to compensate measurements from reference surfaces. Once all the gears were measured, the mean surface

roughness for each gear is plotted in the order of machining. Figure 17 shows the measurement values from the CMM

3.5 Acoustic testing in final assembly

Gears which are determined to pass final test are assembled into transmissions and sent through the audio and functionality tests that determines if the build is good or not. Any gears that are determined too noisy to be in a transmission are caught here and a root cause analysis is performed to determine the reason for failure. If the gears are suspect during the measurement phase, the gears may be used in a test transmission as a lessons learnt test. This testing is used to set limits and identify quality issues that can be caught in the machining process and prevent the same defects from repeating.

CHAPTER FOUR

EXPERIMENTS AND DATA GATHERING

4.1 Grinding wheel description

The study involves the analysis of a grinding process with 34 parts per dressing cycle. The sample size is evaluated with the size of the population given by the total number of parts machined with one tool. Since the standard deviation and mean for the gear geometries are unknown, Slovin's formula given in equation 2 is used to calculate the required number of parts in order for the study to be statistically significance

$$n = \frac{N}{1+N*E^2} \quad (2)$$

Where n is the desired sample size, N is the size of the population and E is the margin of error or error tolerance

The sample size per tool is evaluated to be around 358 parts This translates into a sample of approximately 4 parts per dressing cycle The grinding machine was programmed to separate parts 1, 3, 4 & 34 of the dressing cycle. Part 1 represents the free/unsupported end of the grinding wheel while part 34 represents the fixed end of the grinding wheel. Parts 3 and 4 are towards the free end.

A new wheel was installed and the operators were trained to stack the required parts separate from regular production. A total of 313 gears were obtained and a 4 tooth lead and profile measurement was done to evaluate the quality of the gears.

4.2 Machining and gear data

The vibration monitoring system resolves the measured amplitudes from the time domain into the frequency domain as a Fast Fourier Transform (FFT signal). The measurement system is programmed to resolve the data into 850 discrete frequency points with a chosen resolution of 3.015 Hz. The resolution is chosen in order to obtain frequency information ranging from 0 Hz to 2652.75 Hz in order to have a spectrum wide enough to capture the most common mesh order frequencies and abnormal frequencies that are potential failures during the end of line testing.

To get an overall picture of how the vibration signals look over the tool life, a matlab tool was programmed to display a combined vibration signature. In a paper by Sek [27], a method of representing the frequency in 3 axes was recommended.

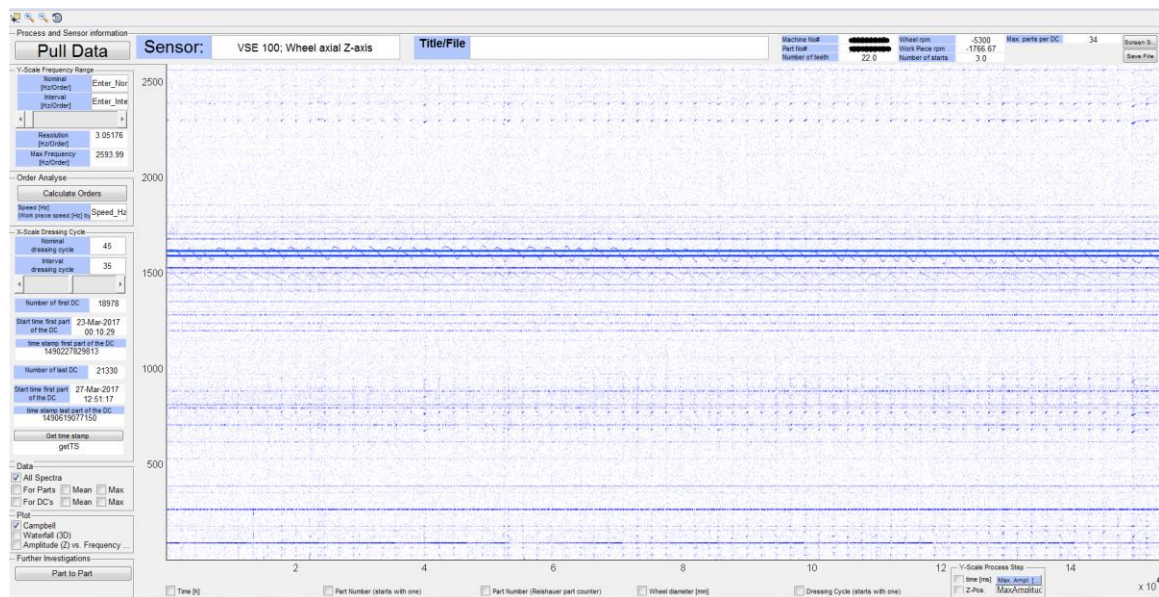


Figure 19: 2-D view of vibration amplitudes vs Frequency Spectra

This representation can be seen in Figure 20 which displays the frequency in the x axis, time in the y axis and the amplitude in the z axis and can be utilized when the harmonic components of a signal are known. Since the all the parameters required to evaluate the harmonics of the system are known, this is a suitable method of plotting the frequency domain data. Additionally, the option to view any two axes makes the analysis of data simpler and clearer (See Figure 19).

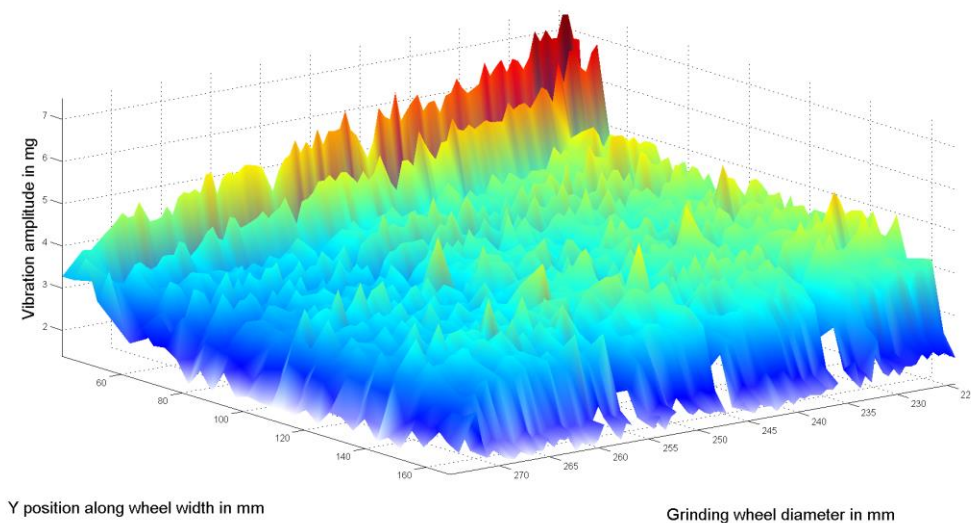


Figure 20: 3-D view of grinding wheel dimensions vs vibration amplitude

The gears are measured on CMMs designed to measure geometrical deviations on gears. Using a four tooth check provides a wide range of measurements for the profile and lead such as angle deviations, form deviations, surface roughness and tooth modifications such as crowning and profile twist. These values are output onto gear diagrams as shown in Figure 17 and saved in excel files for further analysis.

The noise measurement is performed on a specialized test bench designed for gearbox acoustic emissions and cycled through a wide range of operating conditions before being accepted or rejected. The results of the test bench are stored in decibels (dB) corresponding to certain test conditions.

CHAPTER FIVE

DATA ANALYSIS

5.1 Vibration Analysis

From the literature review, the possible frequencies of interest in the analysis are:

- a) The meshing frequency of the work-piece and grinding wheel as that is the typical location of high excitation during regular machining
- b) A deviant frequency that is seen on gears during the end of line measurement that causes the gear pair to fail during final test.

Since this study aims at analyzing the variations in vibrations during the grinding process, Equation 3 is used to evaluate the grinding wheel mesh frequency for the two tool studies. The frequencies vary due to a change in the grinding wheel RPM and the number of starts in the grinding wheel

$$\text{Grinding wheel mesh frequency} = \frac{\text{Grinding wheel RPM} \times \# \text{ of starts}}{60} \quad (3)$$

The process parameters for this study are:

- A grinding wheel RPM of 5300
- A grinding wheel with 3 starts

Using these variables in equation 1, the grinding wheel mesh frequency is calculated to be 265 Hz. The resolution of the measurement sensor results in 265.43 Hz as the closest recorded frequency.

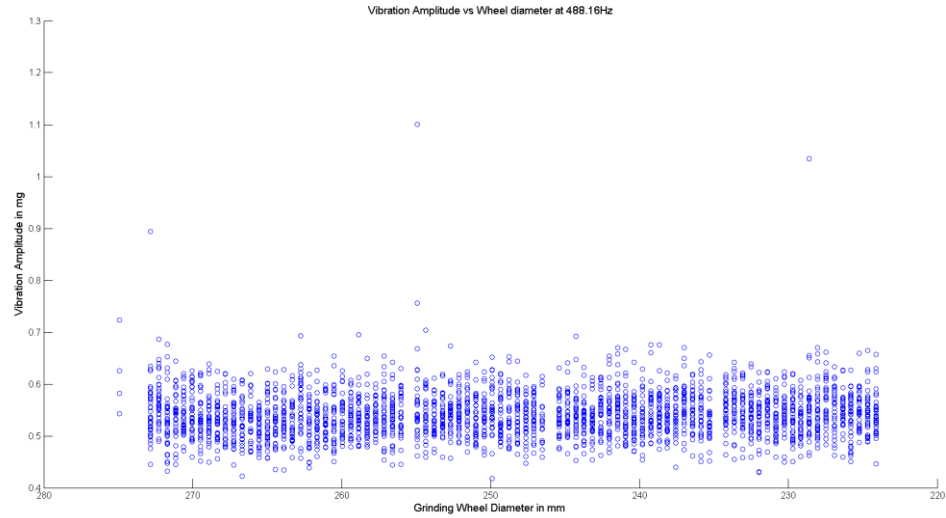


Figure 21: Vibration amplitude at 488.16 Hz (Non-critical frequency)

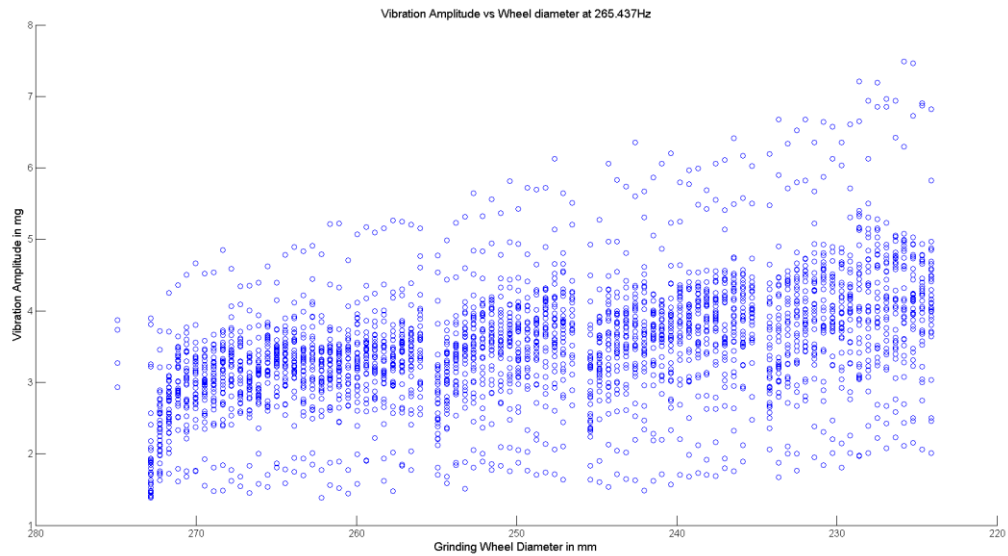


Figure 22: Vibration amplitude at 265 Hz (Grinding wheel mesh frequency)

The two Figures 21 and 22 show that the variation of vibration amplitudes is larger when evaluated at the grinding wheel mesh frequency of 265.43 Hz when compared to a random frequency of 488.16 Hz which represents the base noise level. This is in good

agreement with the literature reviewed [1,12,29] and provides a good frame of reference to analyze the frequencies obtained from the FFT output of the vibration sensors.

The vibration data is graphed in Figure 23 to visualize of the change in measured amplitude in relation to the grinding wheel diameter (d) and the y position along the grinding wheel width (y). The x axis shows y incrementing in mm and the y axis shows d incrementing in mm with the z axis representing the amplitude of vibrations measured in mg.

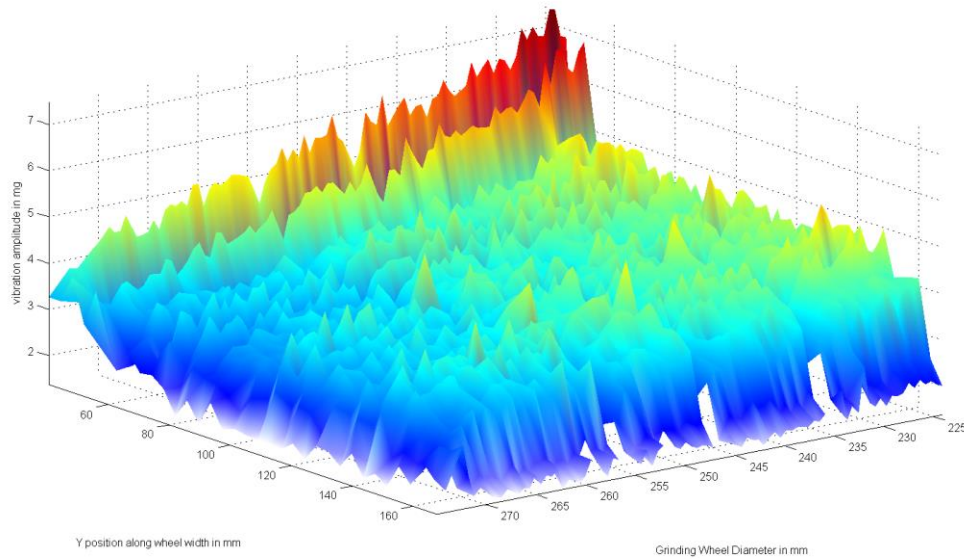


Figure 23: Change in vibration amplitude over wheel width and diameter

To understand the rise in vibrations at each y value, the correlation coefficient is evaluated between the vibration amplitude and grinding wheel diameter for each y. The results are shown in Figure 24



Figure 24: Correlation of vibration amplitude to grinding wheel diameter for unique y values

The correlation coefficients evaluated show that there are some y positions that do not experience a large vibration change over the tool life while other sections have a strong

negative correlation with the tool life. The plots show that at $y = 44.29$ mm and $y = 52$ mm, the correlation is the strongest allowing the interpretation that the vibration amplitudes increase linearly with a decreasing diameter. Some of the more stable sections of the wheel are $y = 40.45$ mm, $y = 48.16$ mm and $y = 167.5$ mm. This is seen with the lowest values of correlation coefficients indicating the vibration amplitudes are largely unchanged over the lifetime of the wheel. Another way of looking at the vibration amplitudes is to split them by dressing cycle. This analysis is covered in Appendix A.

In order to determine if the mean values of the vibrations experienced at each y position are different from each other, two ANOVA tests are performed on the vibration amplitudes recorded at each y position. The first test determines if the variances of the samples are equal and the second test uses the results of the first test to determine which ANOVA must be used.

The hypothesis for the ANOVA are:

H_o : The mean vibration amplitudes in mg are the same at all y positions

H_a : The mean vibration amplitude in mg is different at at least one y position

Source	SS	df	MS	F	Prob>F
Groups	1269.41	33	38.4668	132.39	0
Error	823.44	2834	0.2906		
Total	2092.85	2867			

Figure 25: ANOVA test showing the vibration amplitudes are different over y

The results of the ANOVA on the vibration amplitudes at different y positions is listed in Figure 25. The test statistic of 132.39 and P-value = 0 give us sufficient evidence

to reject the null hypothesis with a 95% level of confidence and claim that at least one y position experiences a different vibration amplitude over the lifetime of the grinding wheel

The boxplot (Figure 26) of vibrations recorded at each y position shows a higher amplitude measured at y_2 and y_4 and a lower amplitude measured at y_{33} and y_{34} . A statistical comparison using the multi-compare tool (Figure 27) in matlab shows that the mean vibrations recorded at these positions are significantly different from each other.

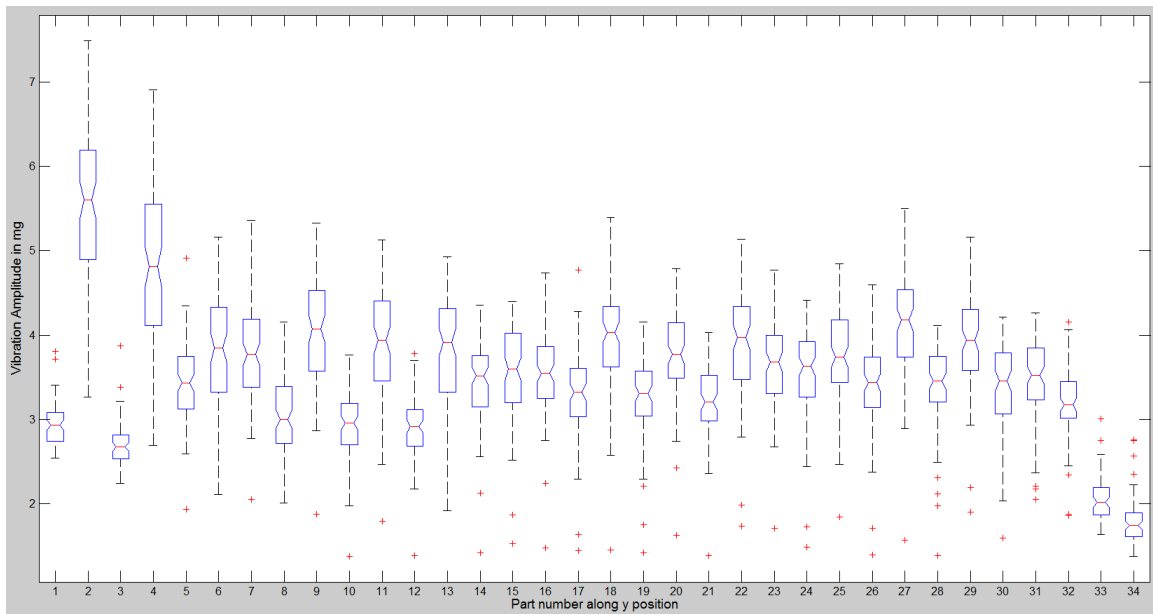


Figure 26: Comparison of vibration amplitudes between all y positions

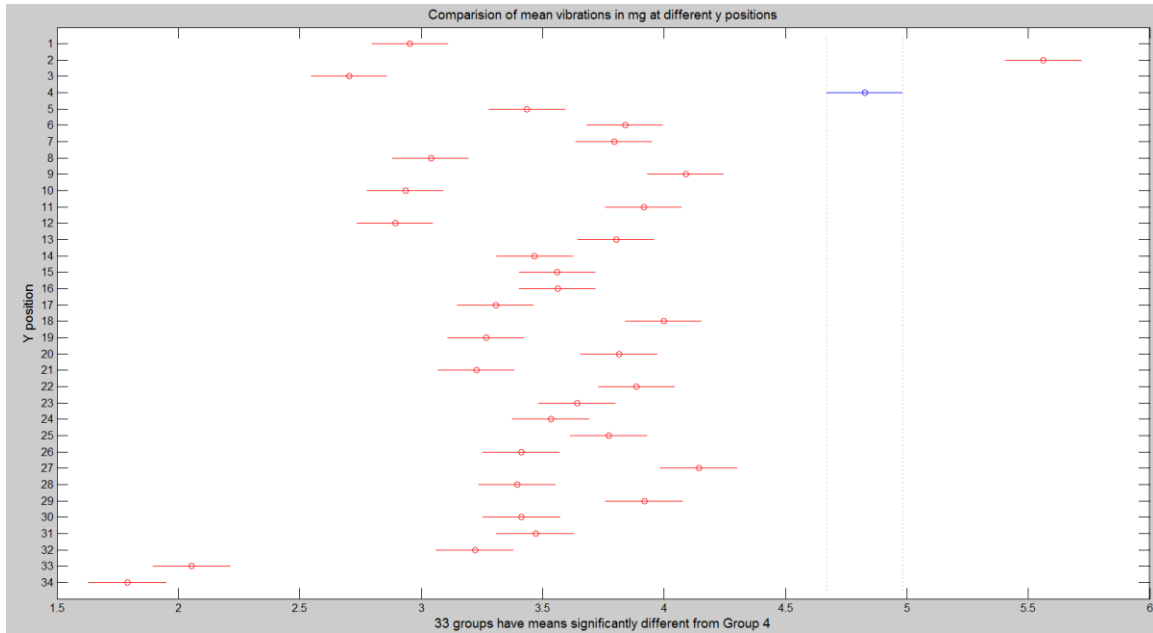


Figure 27: Statistical difference between vibrations at different y positions

Using this inference, a statistical test is performed to determine if the mean vibration amplitude measured at y4 is greater than the mean vibration amplitude measured at y34. The hypothesis for this test is

H_0 : Over a decreasing wheel diameter, the mean grinding wheel vibration in mg at y4 is less than or equal to the vibration measured at y34

H_a : Over a decreasing wheel diameter, the mean grinding wheel vibration in mg at y4 is greater than the vibration measured at y34

The result of the two sample t test, assuming unequal variances returns a p value = 0. This gives us sufficient evidence at a 95% level of confidence to reject the null hypothesis and claim that the mean vibration amplitude of the grinding wheel at 265 Hz is

greater at y4 when compared to the vibration amplitude measured at y34. The boxplots for the distributions are shown in Figure 28

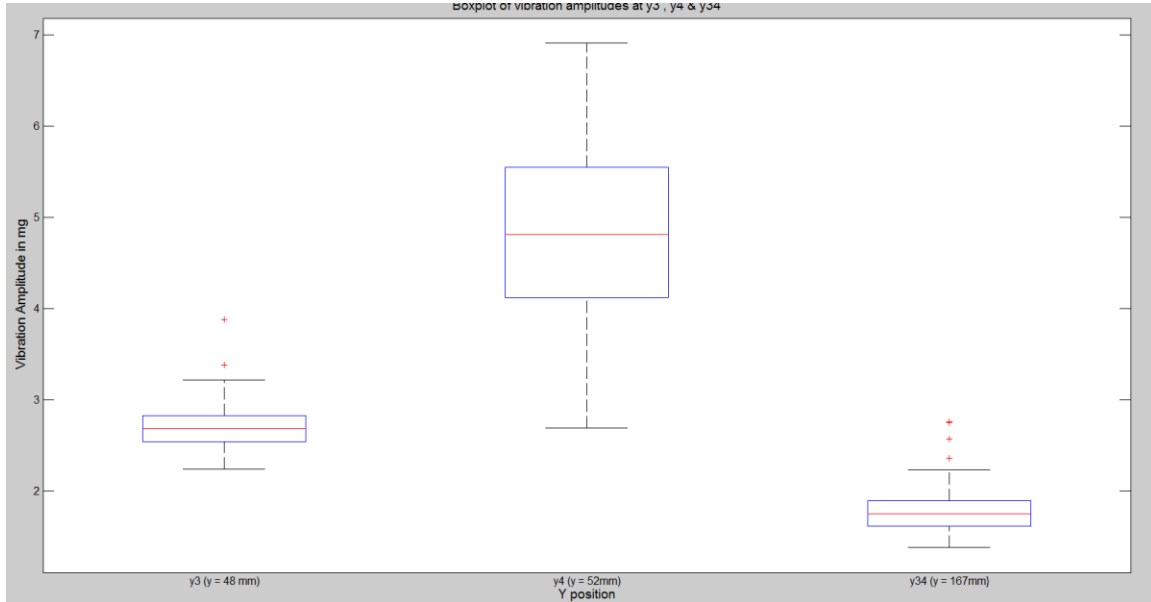


Figure 28: Boxplot of vibration amplitudes at y3, y4 and y34

A similar hypothesis is setup to compare vibration amplitudes on the grinding wheel between y3 and y4. This gives us a control value of y positions next to each other but different correlation coefficients for the change in vibration over the grinding wheel diameter.

H_0 : Over a decreasing wheel diameter, the mean grinding wheel vibration in mg at y4 is less than or equal to the vibration measured at y3

H_a : Over a decreasing wheel diameter, the mean grinding wheel vibration in mg at y4 is greater than the vibration measured at y3

The test statistic is evaluated to be -19.59 and the p value = 0. This gives us sufficient evidence at a 95% level of confidence to reject the null hypothesis and claim that

the mean vibration amplitude of the grinding wheel at 265Hz is greater at y4 when compared to y3. This is shown in Figure 28.

To test if the difference there is a difference in vibration between the free and fixed end even if the correlation coefficient is low, the following hypothesis compares the vibration amplitudes between positions y3 and y34.

H_0 : Over a decreasing wheel diameter, the mean grinding wheel vibration in mg at y3 is less than or equal to the vibration measured at y34

H_a : Over a decreasing wheel diameter, the mean grinding wheel vibration in mg at y3 is greater than the vibration measured at y34

The test statistic is 22.22 and the p value = 0. This gives us sufficient evidence at a 95% level of confidence to reject the null hypothesis and claim that the mean vibration amplitude of the grinding wheel is greater at y3 when compared to y34. This is shown in Figure 28

5.1.1 Vibration analysis conclusion

To conclude the analysis on vibration comparison

Table 1: Vibration analysis conclusions

	Vibration Amplitude (mg)	Computed difference (mg)
y4 - y34	4.82 - 1.79	3.036
y4 - y3	4.82 - 2.7	2.1218
y3 - y34	2.7 - 1.79	0.9142

- Mean vibrations are higher at y4 when compared to y34 with a computed difference of 3.035 mg
- Mean vibrations are higher at y4 when compared to y3 with a computed difference of 2.12 mg
- Mean vibrations are higher at y3 when compared to y34 with a computed difference of 0.912 mg

5.2 Gear geometry analysis

The next step is to determine if the parts machined at these positions on the grinding wheel have similar deviations in the surface roughness of the gear profile. The samples are collected as explained in chapter 4 and a set of parts that are all machined at specific y positions are measured. The following hypothesis is setup to determine if there is change in the roughness of these parts. Since the gear measurement involves 2 flanks, a separate hypothesis has to be formulated for each flank.

H_o : The surface roughness of the left profiles machined at y4 (4.82 mg) are less than or equal to the surface roughness of the left profiles machined at y34 (1.79 mg)

H_a : The surface roughness of the left profiles machined at y4 are greater than the surface roughness of the left profiles machined at y34

The test statistic is calculated to be 5.76 and the p value = 0. This gives us sufficient evidence at a 95% confidence level to reject the null hypothesis and conclude that the surface roughness of the left profiles is rougher when machined at y4 when compared to y34. The boxplot in Figure 29 shows the difference in vibration amplitudes for the two positions

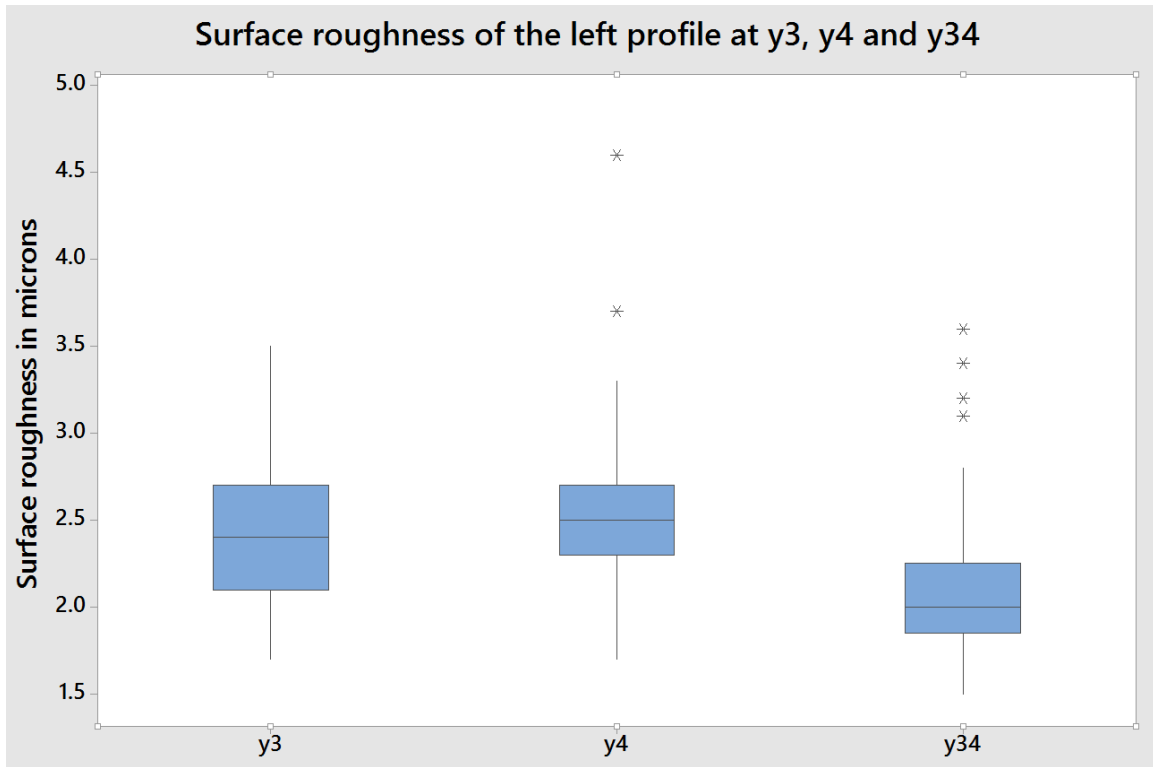


Figure 29: Boxplot of surface roughness for the left profiles

A similar hypothesis is used to determine if the profiles of the right flank differ in roughness and is stated as:

H_o : The surface roughness of the right profiles machined at y4 (4.82 mg) are less than or equal to the surface roughness of the right profiles machined at y34 (1.79 mg)

H_a : The surface roughness of the right profiles machined at y4 are greater than the surface roughness of the right profiles machined at y34 by

The test statistic is -4.38 and the p value = 1 therefore there is insufficient evidence at a 95% level of significance to claim that the surface roughness of the right profile is greater at y4 when compared to y34

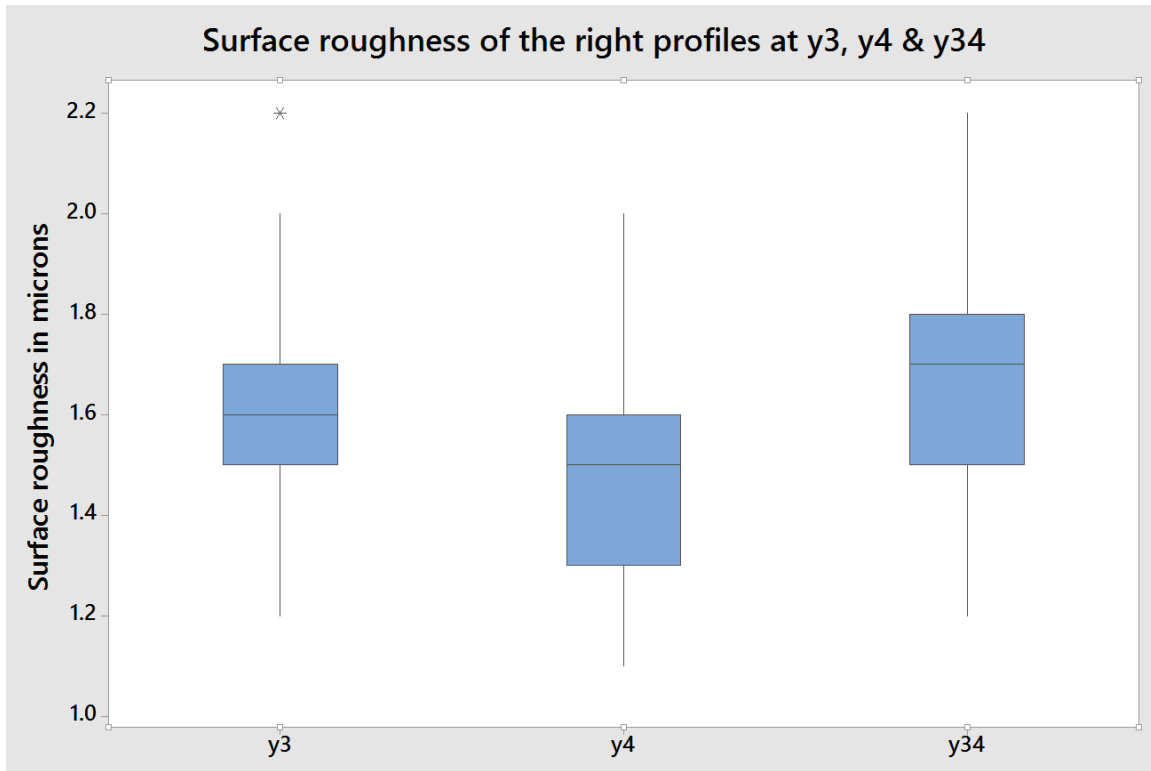


Figure 30: Boxplot of the surface roughness of the right profiles

The result of the hypothesis test for the right profile comparison actually shows the profiles ground at y34 are rougher than the profiles ground at y4. This contradicts the theory that when rougher profiles are ground, the vibration amplitudes also rise. In order to test if the gear profiles at y34 are really rougher than the gear profiles at y4, a statistical comparison is made between the left gear profiles machined at y4 and the right gear profiles machined at y34. The hypothesis for this is

H_o : The surface roughness of gears machined at y4 (4.826 mg) is less than or equal to the surface roughness of gears machined at y34 (1.79 mg)

H_a : The surface roughness of gears machined at y4 (4.826 mg) is greater than the surface roughness of gears machined at y34 (1.79 mg)

The test statistic equals 14.53 and the p value = 0. This allows us to reject the null hypothesis with a 95% level of confidence and claim that the surface roughness of the left profile machined at y4 is greater than the surface roughness of the right profile machined at y34. This conclusion shows that even though the right profile is machined rougher at y34 when compared to y4, the overall roughness of the gears machined at y4 is higher than those machined at 34.

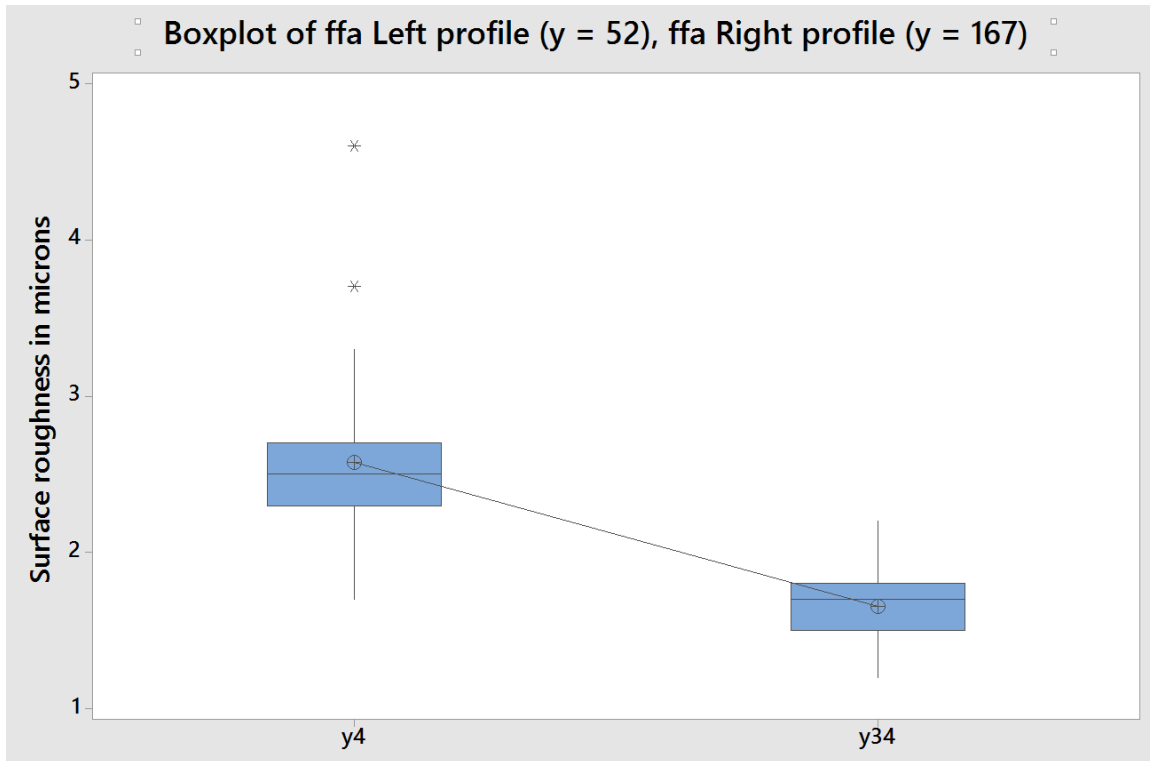


Figure 31: Comparison of the left and right surface roughnesses between y4 and y34

Similar to the comparison of vibration amplitudes, the following hypothesis tests for differences between surface roughness of parts machined at y3 and y4.

H_o : The surface roughness of the left profiles machined at y4 (4.82 mg) are less than or equal to the surface roughness of the left profiles machined at y3 (2.7 mg)

H_a : The surface roughness of the left profiles machined at y4 (4.82 mg) are greater than the surface roughness of the left profiles machined at y3 (2.7 mg)

The test statistic is -2.32 and the p value = 0. This allows us to reject the null hypothesis with a 95% level of confidence and claim that the surface roughness of the left profile is higher when machined at y4 when compared to y3 as shown in Figure 29

The hypothesis comparing the right profiles for parts machined at y4 and y3 states

H_o : The surface roughness of the right profiles machined at y4 (4.82 mg) are less than or equal to the surface roughness of the left profiles machined at y3 (2.7 mg)

H_a : The surface roughness of the right profiles machined at y4 (4.82 mg) are greater than the surface roughness of the left profiles machined at y3 (2.7 mg)

The test statistic is 3.68 and the p value =1. Therefore there is insufficient evidence to reject the null hypothesis at a 95% level of confidence and claim that the right profiles machined at y4 are rougher than the right profiles machined at y3. However, since the p value is 1, testing the hypothesis that the right profiles machined at y3 are rougher than those machined y4 results in a p value of 0 and gives confidence in the claim that the right profiles machined at y3 are rougher than the right profiles machined at y4.

The next comparison of surface roughness is between parts machined at y3 and y34. The hypothesis testing the differences between the left profile roughness of parts machined at these locations on the grinding wheel is:

H_o : The surface roughness of the left profiles machined at y3 (2.7 mg) are less than or equal to the surface roughness of the left profiles machined at y34 (1.79 mg)

H_a : The surface roughness of the left profiles machined at y3 (2.7 mg) are greater than the surface roughness of the left profiles machined at y34 (1.79 mg)

The test statistic is calculated to be 3.89 and the p value = 0. This allows us to reject the null hypothesis with a 95% level of confidence and claim that the surface roughness of the left profiles machined at y3 are rougher than the surface roughness of the left profiles machined at y34

To compare the right profiles of the parts machined at these locations, the hypothesis states

H_o : The surface roughness of the right profiles machined at y3 (2.7 mg) are less than or equal to the surface roughness of the right profiles machined at y34 (1.79 mg)

H_a : The surface roughness of the right profiles machined at y3 (2.7 mg) are greater than the surface roughness of the right profiles machined at y34 (1.79 mg)

The test statistic is calculated to be -1.05 and the p value is 0.853. Therefore we fail to reject the null hypothesis with a 95% level of confidence and there is insufficient evidence to claim that the surface roughness of parts machined at y3 are greater than the surface roughness of the parts machined at y34

5.2.1 Gear geometry analysis conclusion

To conclude the analysis on surface roughness

Left profile conclusions

Table 2: Left profile roughness conclusion

Left Profile roughness	Surface roughness (μm)	Computed difference (μm)
y4 - y34	2.57 – 2.11	0.46
y4 - y3	2.57 – 2.4	0.17
y3 - y34	2.4 – 2.11	0.29

- The surface roughness of the left profile is greater when machined at y4 when compared to y34 with a computed difference of 0.46 microns
- The surface roughness of the left profile is greater when machined at y4 when compared to y3 with a computed difference of 0.17 microns
- The surface roughness of the left profile is greater when machined at y3 when compared to y34 with a computed difference of 0.29 microns

Right profile conclusions

Table 3: Right profile roughness conclusion

Right Profile roughness	Surface roughness (μm)	Computed difference (μm)
y4 - y34	1.47 – 1.65	- 0.18
y4 - y3	1.47 – 1.61	- 0.14
y3 - y34	1.6 – 1.65	- 0.05

- The surface roughness of the right profile is greater when machined at y34 when compared to y4 with a computed difference of 0.175 microns
- The surface roughness of the right profile is greater when machined at y3 when compared to y4 with a computed difference of 0.198 microns
- No statistical comparison can be made between the roughness of the right profiles machined at y3 and y34.

5.3 Noise Measurement

The final test in the process is the noise made by the gear pair under load. To determine if there is a difference, the hypothesis tests if the noise made by the gear pair at the mesh frequency is higher for gears machined at y4 when compared to gears machined at y34

H_o : Is the noise made by gears machined at y4 less than or equal to the noise of gears machined at y34

H_a : Is the noise made by gears machined at y4 greater than the noise of gears machined at y34

The test statistic is calculated to be 1.97 and the p value = 0.026. This gives us sufficient evidence at a 95% level of confidence to reject the null hypothesis and conclude that the noise made by gears machined at y4 is greater than the noise made by gears machined at y34.

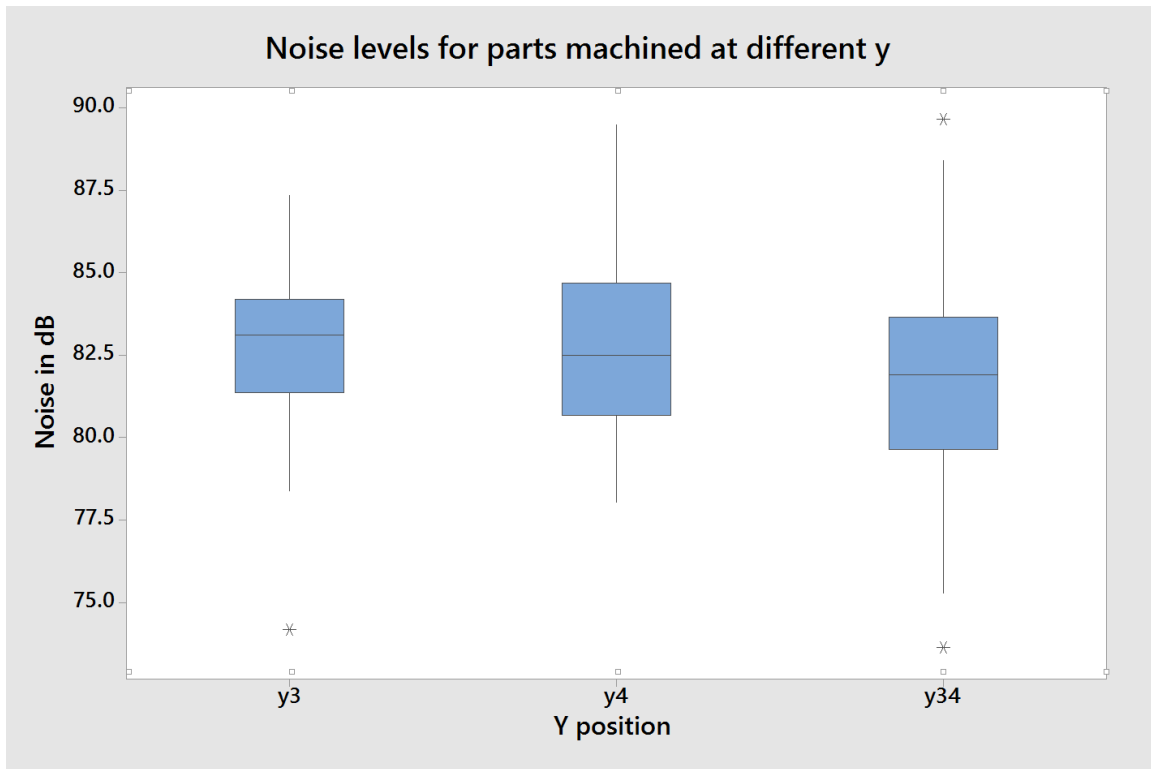


Figure 32: Boxplot for noise made by gears machined at y3, y4 and y34

A similar hypothesis tests the variation in noise made by gears machined at y4 and y3

H_o : Is the noise made by gears machined at y4 less than or equal to the noise of gears machined at y3

H_a : Is the noise made by gears machined at y4 greater than the noise of gears machined at y3

The test statistic is calculated to be 0.27 and the p value = 0.607. This is insufficient evidence at a 95% level of confidence to reject the null, and we cannot claim that the noise made by gears machined at y4 is different from gears machined at y3.

The following hypothesis tests the variation in noise made by gears machined at y3 and y34

H_o : Is the noise made by gears machined at y3 less than or equal to the noise of gears machined at y34

H_a : Is the noise made by gears machined at y3 greater than the noise of gears machined at y34

The test statistic is 2.28 and the p value = 0.012. This gives us sufficient evidence to reject the null with a 95% level of confidence and claim that the noise made by gears machined at y3 is greater than the noise made by gears at y34

5.3.1 Noise analysis conclusions

To conclude, the analysis of the noise made by gears machined at different sections of the wheel show that

Table 4: Noise conclusions

	Noise (dB)	Computed difference (dB)
y4 - y34	82.83 – 81.74	1.09
y4 - y3	82.83 – 82.96	0.13
y3 - y34	82.96 – 81.74	1.22

- Gears machined at y4 are louder than gears machined at y34 and the difference is computed to be 1.09 dB
- There is no significant difference in noise made by gears machined at y3 and y4
- Gears machined at y3 are louder than gears machined at y34 and the difference is computed to be 1.21 dB

CHAPTER SIX

CONCLUSION AND FUTURE WORK

6.1 Conclusions

A new grinding wheel was installed in a gear grinding machine and used till it was completely worn out. Vibration amplitudes were measured over the entire tool life and gears were sampled at fixed y positions while the wheel diameter decreased. The vibration signals were evaluated using the FFT algorithm and the sampled gears were measured on a CMM to evaluate the geometries machined. Finally, the gears were assembled into gearboxes and the noise made by the gear pair was measured. The results answer the following research questions:

1. Is there a variation of vibration measurements that correlate to the variables of the grinding wheel?

There is a correlation between vibration amplitude and decreasing grinding wheel diameter for certain y positions. Positions y4, y2 and y6 show the highest correlation between vibration amplitude and grinding wheel diameter with coefficient of determination values of 0.92, 0.90 and 0.88 respectively.

Additionally, the vibration amplitude was the highest at y2 with an amplitude of 5.56 mg, followed by y4 with an amplitude of 4.82 mg. The vibration amplitudes were the least at y34 with an amplitude of 1.79 mg followed by y33 with an amplitude of 2.05 mg

2. Is there a variation in the gear geometries that correlate to the location of machining on the grinding wheel?

Based on the y positions with a higher vibration amplitude, the left profile roughness is higher. When gears are machined with an average vibration amplitude of 4.82 mg at y4, the average left profile roughness is 2.57 microns and when the average vibration amplitude drops to 1.79 mg at y34, the average left profile roughness is 2.11 microns.

3. Is there a variation in the noise made by gears that correlate to the location of machining on the grinding wheel?

The gears machined at the free end are louder than the gears machined at the fixed end and there is no difference seen in the noise made between gears machined at the free end. The gears machined at y4 make 82.83 dB of noise while gears machined at y34 make 81.74 dB of noise

6.2 Future work

To evaluate the process further, different y positions may be selected to determine if the results are similar. This will also lead to a better understanding of the tool behavior and decisions may be made regarding specific y positions or diameter values. Variability in the manufacture of the tool can also be reduced by repeating the study with similar sample selection

The study can be repeated on other processes to determine if they are stable through all variables of the grinding wheel. This will generate more knowledge about the gear grinding process and eliminate sources of variation such as previous machining steps.

Another way of testing the tool is to obtain samples for CMM measurement and noise testing based on the dressing cycle as explained in Appendix A. This will point to variation in vibrations due to changing wheel diameter for all y positions. Using this combination of data may identify unique y and d values that are susceptible to higher excitation of the tool. This can be programmed into the gear grinder and avoid machining parts at these sections and reduce the cost of quality at the machining process.

The number of data collected and the speed at which data is collected may be increased by using the failures at the end of line testing as a sample rather than monitoring all processes. The machines and gears with a high end of line failure rate can be evaluated geometrically and the vibration data can be extracted to draw meaningful conclusions. This will complete the data circle and draw conclusions about future failures for similar noise conditions.

Finally, the collection of vibration data can result in the creation of an envelope curve that sets a bound of vibration amplitude for all frequencies measured. This will be a limit that trips the machine into classifying the part as scrap and preventing it from being processed further. These envelope curves can constantly be updated with data received from end of line testing and geometrical data to ensure that false scrap is not created.

CHAPTER SEVEN

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APPENDICES

APPENDIX A: Analysis based on grinding wheel diameter

As mentioned in chapter five, the data can be analyzed over the grinding wheel diameter with a changing y . Figure XX shows the boxplots of the vibration amplitudes for all parts machined at a particular dressing cycle.

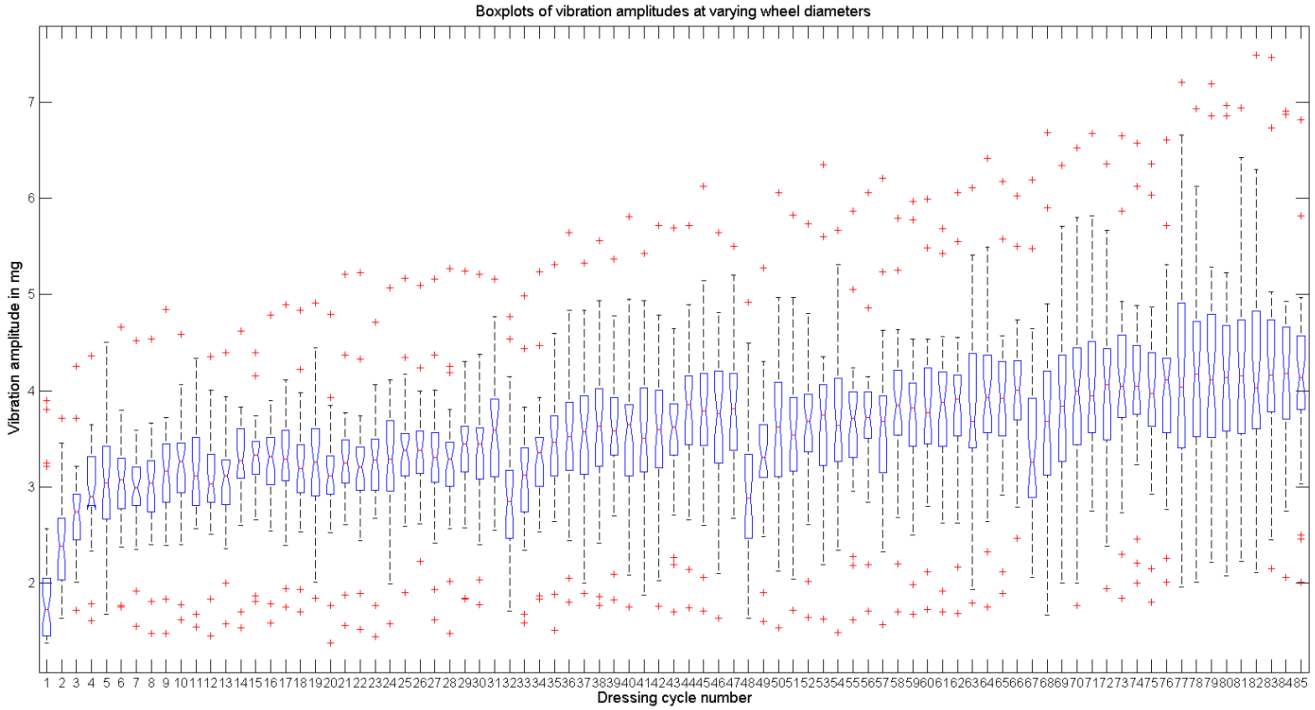


Figure A1: Boxplot for vibrations by dressing cycle (d value)

This shows that the vibration amplitudes on the grinding wheel tend to increase with a decreasing wheel diameter. To test the claim that the wheel vibrates more when the diameter reduces, the following hypothesis is tested:

H_0 : The mean vibration on the grinding wheel at dressing cycle 85 is lower than or equal to the mean vibration on the grinding wheel at dressing cycle 1

H_a : The mean vibration on the grinding wheel at dressing cycle 85 is higher than the mean vibration on the grinding wheel at dressing cycle 1

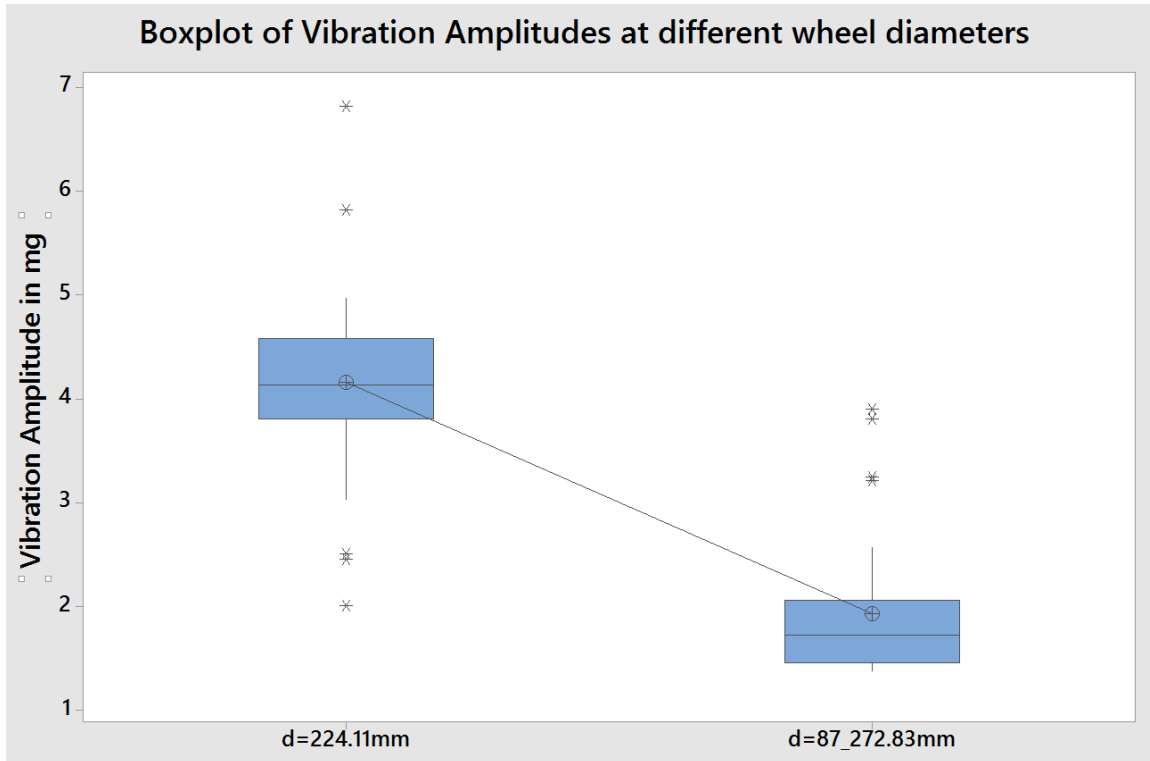


Figure A2: Boxplot of vibration values at start and end of tool life

The test statistic is 11.73 and the p value = 0. This gives us sufficient evidence at a 95% level of confidence to reject the null and claim that the vibration on the grinding wheel is higher when the diameter is smaller. Figure XX shows the boxplot of the two values and the difference in mean vibrations is evaluated to be 2.28 mg.

The future scope of this result will be to select all parts from the above two dressing cycles and determine if the geometrical finish and the noise made by these gears are similarly different.